LB-85

THE DECAY AND RECOVERY OF THE PULSED EMISSION OF OXIDE-COATED CATHODES

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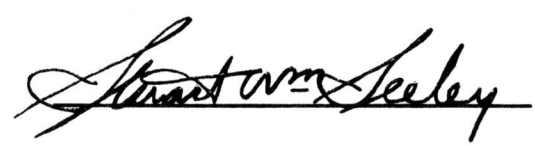
Approved



ABSTRACT

The decay and recovery of the pulsed emission of cathodes consisting of BaO on nickel is studied. The emission of the cathodes is measured in diodes of cylindrical geometry having water-cooled copper anodes spaced 0.019 inch from the cathode.

Most of the diodes show a decay of anode current when first put in pulse operation. Decays of 2 - 50 per cent are observed during 150 microsecond pulses. The decay tends to disappear when the tubes are aged under pulse conditions. The peak current is a linearly decreasing function of the logarithm of the duty cycle, even when there is no perceptible decay during the pulses. The rate of decrease is independent of the pulse repetition rate and decreases with cathode temperature.

Current-voltage characteristics during the pulse and recovery periods are obtained by short sampling pulses. A comparison of these characteristics with computed ideal characteristics does not discriminate unambiguously between a variation of emission and a variation of internal cathode impedance as a source of current decay. Studies to separate the contributions of these effects are in progress.

The Decay and Recovery of the Pulsed Emission of Oxide-Coated Cathodes

Introduction

It is a common observation that the pulsed and dc emissions from an oxide cathode in an ordinary vacuum tube differ by about an order of magnitude. By the exercise of great care, Fan[1] has been able to achieve the same current from an oxide cathode under dc and pulse conditions at cathode temperatures under 1000°K, and Fineman and Dillinger have achieved dc emissions in excess of 10 amperes per square centimeter at temperatures over 1000°K.[2] However, even with careful attention to choice of materials and cleanliness, marked differences in dc and pulse currents are found. In these tubes, even if no decay is observed in microsecond pulses, it seems certain that the initial high current on application of a "unit function" voltage must decrease to the dc value. R. L. Sproull has studied the form of this decay under pulse conditions.[3] He suggests that the decay may be due to the electrolytic depletion of a barium layer at the surface of the cathode. However, other hypotheses which do not involve changes in the emitting surface lead to the same form of decay.

It is the object of the present study to locate the source or sources of decay. Because any satisfactory theory of decay must also account for the recovery of emission, a considerable portion of the effort has been devoted to the investigation of recovery rates. While the primary object has yet to be realized, a report on some of the pulse measurements may be of interest to other workers in the field. The data have also been found to be of practical value in that they provide a basis for estimates of the emission available when a cathode is subjected to groups of pulses, as in coded-pulse communications systems.

Measurements have been made of the variation of peak current with pulse length and repetition rate, of the decay of current when a "unit function" voltage is applied, and of the rate of recovery, the last by application of narrow sampling pulses subsequent to relatively long pulses. These sampling pulses have been used to measure current-voltage characteristics during decay and recovery periods in an attempt to distinguish between emission failure and an increase of internal cathode impedance. To be significant, these characteristics must be determined in a time short compared with the decay or recovery periods of the cathode. This consideration restricts the design of measuring circuits and experimental diodes.

Test Diodes

The electrical design of the test diodes for emission measurements is circumscribed by three major factors; bandwidth, dissipation, and power supply regulation. The inevitable stray capacitances in the measuring circuits make it necessary to work at low impedance levels if the true voltage and current waveforms are to be observed when microsecond pulses are employed. This implies that the cathode under study should have an area large enough to deliver currents of the order of amperes. On the other hand, if the cathode area is made very large, the cost of a power supply which will deliver the required pulse current at constant voltage becomes prohibitive. When the current density from a cathode is high, as it is under pulse conditions, the instantaneous dissipation density at the anode is also high. If the duty exceeds a fraction of a percent, average dissipation becomes large and anode design a problem. This difficulty can be alleviated in part by using a close-spaced tube so that the tube voltage drop is small. Even so, the dissipation problem is such that water-cooling of the anode is necessary. The use of a close-spaced tube has another advantage when mechanical considerations lead to a cylindrical geometry, in that the diode becomes substantially planar. The theory of planar diodes is well established over the entire range of current from the Boltzmann region to the Schottky region. Hence, the experimental data can be compared with those calculated for an ideal tube. These considerations led to the adoption of a close-spaced, cylindrical diode, with a cathode area of about 0.8 cm^2.

The choice of materials was largely determined by the desire to work, at least initially, with as simple a chemical system as was compatible with commercially available materials. An electrolytic nickel (RCA N-81) was chosen for the cathode base metal, and a single carbonate, $BaCO_3$ (Mallinkrodt Ultrapure) was selected for the coating. To avoid possible contamination by heater insulation, a radiation heater was used. Dissipation considerations dictated the use of a copper anode.

The test diode structure is shown in Fig. 1. The cathode is a seamless nickel cylinder 1 cm long and 0.6 cm in diameter capped by

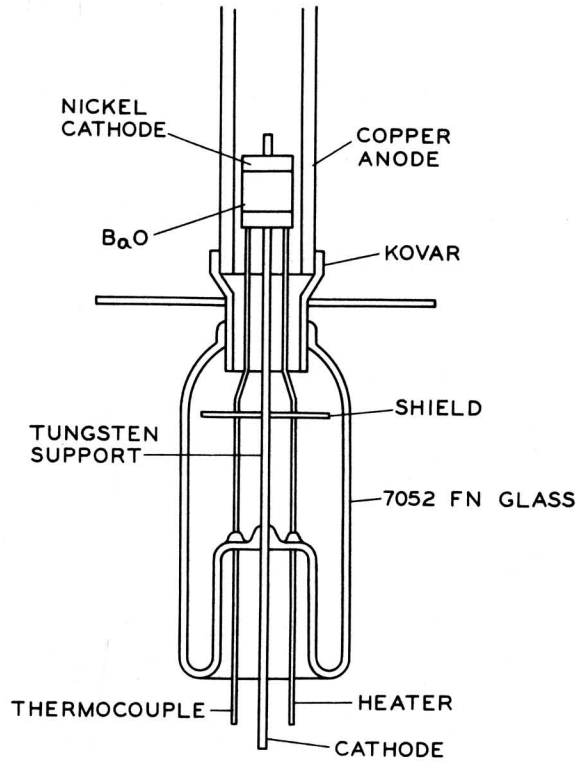


Fig. 1 – Laboratory diode H-4354.

nickel thimbles. A centrally located band 0.4 cm wide is coated with 8 mg/cm^2 of barium carbonate. A molybdenum-nickel thermojunction is welded to the inner wall of the cathode sleeve opposite the center of the coated band. The cathode is heated by a spiral tungsten heater extending almost the full length of the sleeve. The assembly is supported by a heavy tungsten rod along the axis. This rod serves to align the cathode structure accurately within the anode during seal-in. The anode cylinder is made of OFHC copper and has an inner diameter such that the cathode-anode spacing is 0.048 cm. The anode is long enough so that the tube may be sealed off from the vacuum system by a copper pinch-off without disturbing the cathode-anode spacing.

All tubes were exhausted and baked at 300°C until the pressure fell to less than 10^{-7} mm of Hg. The oven was then removed and the cathode heated to approximately 600°K and maintained at that temperature until the pressure fell below 10^{-7} mm of Hg. From this point on, two procedures were used. In the first, the cathode temperature was raised abruptly to 1200°K without regard to pressure. When the pressure again fell to 10^{-7} mm of Hg, the

conversion of the carbonates was considered complete. In the second procedure, the cathode temperature was raised gradually from 600° to 1200°K in such a manner that the pressure never exceeded 10^{-4} mm of Hg. Conversion, as indicated by evolution of gas appeared to be substantially complete by the time a temperature of 1100°K was reached. This process required a period of three to six hours. Both methods produced equally active cathodes.

Activation was carried out by drawing gradually increasing currents. Some cathodes appeared to be fully activated on completion of the carbonate conversion and showed no departure from the 3/2 power law until high current densities were reached. Others proved difficult to activate, gave indication of poisoning when anode voltages greater than 8 or 9 volts were applied, and required prolonged heating and bombardment of the anode before activation was achieved. No satisfactory correlation of cleaning and processing procedures with activation has been possible. However, simple washing in acetone and water appeared to be as good as, or better than, extensive chemical cleaning. In both cases all parts were hydrogen-fired prior to assembly.

Cathode temperatures have not been determined with precision. To avoid complicating the tube structure, the cold junction of the thermocouple was placed inside the tube. Hence thermocouple measurements were used only to reproduce temperatures established by other means. Since the cathode surface is not visible in these tubes, optical pyrometer measurements could not be made. To establish an approximate absolute temperature scale, a substantially identical structure with fine holes in the anode was wholly enclosed in a glass envelope and processed in the normal manner. Observations of cathode temperature as a function of heater power were thus obtained. To minimize errors due to anode heating the exterior of this anode was carbon coated. This, combined with the high reflectivity of the interior surface of the anode, results in small error from this source. This error is such as to make reported temperatures higher than the true temperature. The resulting curve of cathode temperature versus heater power agrees well with the universal curve developed by Haller.[4]

General Observations

For convenience, the term "decay" will be used in a restricted sense. When a tube operated at constant voltage shows a decrease of current during the period of application of the voltage, the tube will be said to show decay. When there is no observable decrease of current during this period, the tube will be said to show no decay, even though the pulse and dc currents may be markedly different.

Before proceeding to a detailed discussion of the measurements on decay and recovery of current in the present diodes, it may be well to note briefly some general observations on the behavior of the diodes. Decay of pulsed emission has been observed with pulses ranging from 5 to 5000 microseconds. It has always been found possible to describe normal decay in terms of the Sproull formula.[5] In all cases, a reduction in cathode temperature has decreased the rate of decay and, at the same time, the peak pulse current has approached the dc value. Aging a cathode under pulse conditions at the maximum current the tube would stand without undue sparking, has caused the disappearance of decay, usually in a period of 30 to 50 hours. Similarly, aging at relatively high (0.3 A/cm²) dc currents or operating the tube as a rectifier at 60 cycles with the same average current has greatly reduced or eliminated decay. On the other hand, prolonged storage with the cathode cold, or aging for short periods on open circuit with the cathode heated, has restored or increased decay. It has been observed that the decay was always decreased immediately following a spark and that prolonged sparking, provided it was not sufficiently violent to destroy the coating, gradually reduced the decay to an undetectable level.

When the pulse length has been varied while holding the repetition rate constant, the maximum pulse current which could be drawn without sparking increased with decreasing pulse length whether or not the tube showed decay. The sparking which established the maximum permissible voltage occurred near the end of the pulse. As the maximum spark-free current was exceeded, the frequency of sparking and the duration of individual sparks increased rapidly toward the end of the pulse.

By means of the thermocouple, it has been possible to observe the cooling of the cathode by electron evaporation when a tube has operated at modest current levels. However, at high current levels, whether on pulse or dc, an increase of cathode temperature has always been observed. It is felt that the few cases of abnormal decay which have been observed may be due to heating of the cathode by pulse currents. In these abnormal cases, the tube current rose during the early part of the pulse and then declined in an apparently normal manner. Tubes showing this abnormality, which was usually transitory, were very prone to spark.

Prolonged aging under pulse or dc conditions has usually resulted in increased peak current. No reduction of decay, other than that caused by a reduction in temperature, has been at the expense of peak current.

Peak Current vs Duty

A possible method of obtaining data on decay and recovery of current in a diode is to observe peak current as a function of duty. This method has two major limitations. First, decay and recovery effects are not separated, so that measurements are difficult to interpret. Second, the construction of pulser and measuring circuits capable of operating over an extremely wide range of duty is a major problem. It is particularly difficult, if, as is desirable, duty is to be varied by changing both pulse width and repetition rate. A further problem is the choice of a suitable anode voltage. It must be low enough so that sparking will not occur at large duties, but at the same time it must be large enough so that the tube current is not limited by space charge alone at small duties. These conditions are frequently not compatible. For these reasons, measurements of this type have been attempted only over limited ranges of duty.

The variation of peak current with duty at constant anode voltage is shown in Fig. 2. In this case the duty has been varied by altering the pulse length while maintaining a constant repetition rate. All tubes examined under these conditions have shown the same form of variation of peak current with duty. Some of these

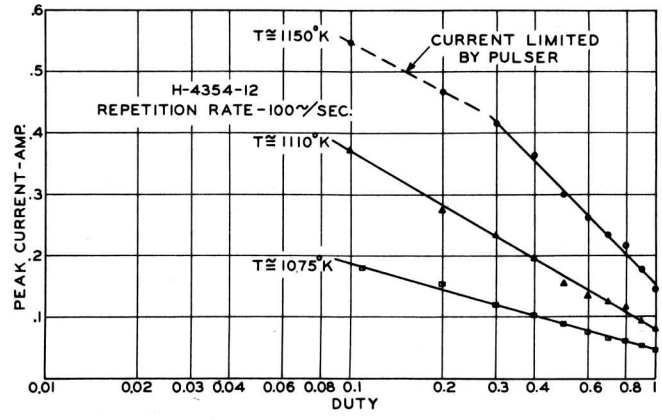


Fig. 2 – The variation of peak pulsed current with duty at various temperatures with a fixed repetition rate.

tubes showed decays of as much as 50 per cent during the pulse; in others no decay was observable. The figure shows measurements at three cathode temperatures and indicates that the rate of change of peak current with duty diminishes rapidly with decreasing temperature. The dashed section of the upper curve in Fig. 2 is not significant because the current was limited by the pulser. Changes of repetition rate over a limited range do not affect the shape or position of these curves. This is brought out in Fig. 3 which shows the variation of peak current with duty from 0.05 to unity duty at three repetition rates.

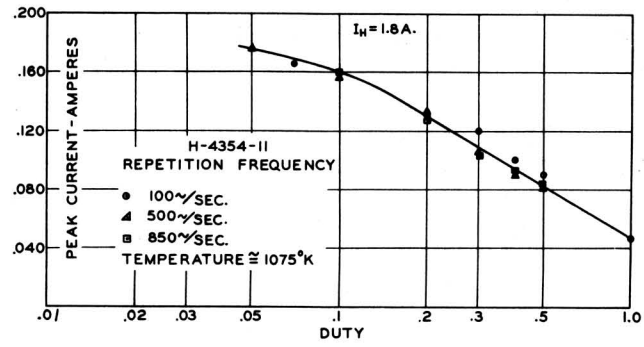


Fig. 3 – The variation of peak pulsed current with duty with various repetition rates.

Plots of peak current versus the logarithm of the duty show an approach to zero slope for duties less than 10 per cent. For sufficiently small duties, the slope must become zero, but present measurements at lower duties have not located the knee of the curve.

A few measurements of "isolated" pulses have been made to determine if the peak currents

at very low duties are indicative of the peak current which may be drawn by application of a "unit function" voltage. The decay of current with time in an "isolated" pulse is shown in Fig. 4. When the interval between pulses was varied from one-half minute to several minutes, the peak current and the rate of decay of current showed no variation. The peak current observed under these conditions was the same as that for a 5-microsecond pulse applied at a repetition rate of 100 per second (0.05% duty).

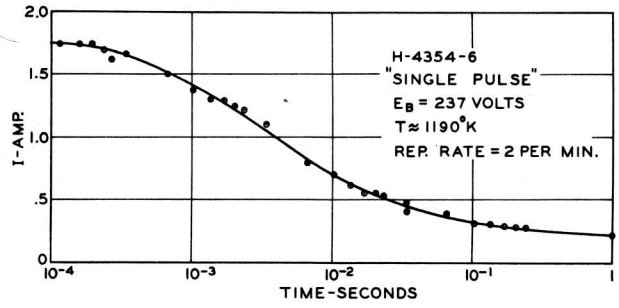


Fig. 4 – The decay of anode current on the application of a constant voltage to the anode.

There are several possible mechanisms which may account for the observed decay and the variation of peak current with duty. Among these are poisoning due to the anode and poisoning due to residual gas, both of which are surface phenomena. Another possibility is the electrolytic transport of barium from the surface as suggested by Sproull. This is, in part, a volume effect but may be observed in a diode as a limitation of the zero-field emission. Further possibilities are changes in coating or interface resistance.

It would be most desirable to distinguish clearly between decays due to zero-field-emission limitation and decays due to changes of coating or interface impedance. If E-I characteristics can be obtained over a sufficiently wide voltage range throughout the decay and recovery periods, it should be possible to make this distinction.

E-I Characteristics during Decay and Recovery

If E-I characteristics are to be significant in interpreting effects during decay and recovery, they must be obtained by measurements which do not perturb the decay and recovery appreciably. In the present diodes, such measurements have been possible, using pulse lengths of 100 to 300 microseconds and repetition rates of the order of 100 cps. To obtain the E-I characteristics during the primary pulse, this pulse was interrupted for approximately 3 microseconds. The interrupting pulse was approximately triangular, the leading edge being very steep. The E-I characteristics were obtained during the period of re-application of anode voltage. Fig. 5 shows the slight effect of such an interrupting pulse on the decay of current in one of the diodes.

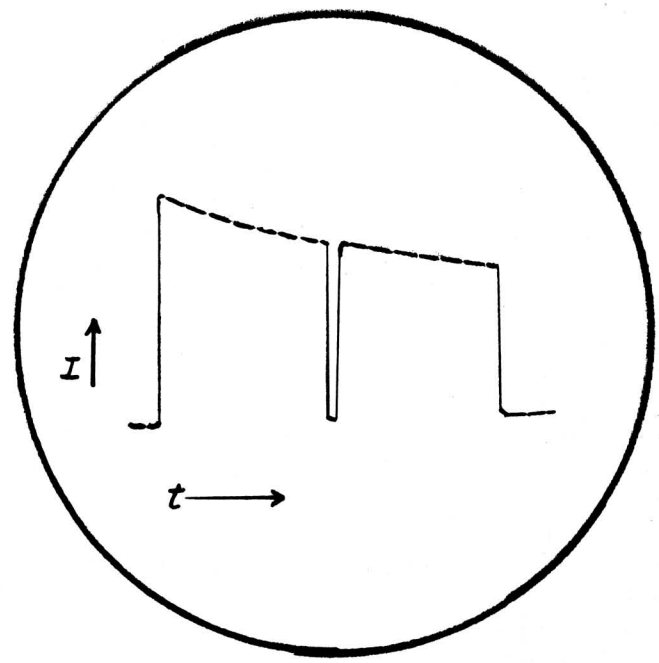


Fig. 5 – An oscilloscope trace showing the decay of anode current during a 145 microsecond pulse with a 3 microsecond interrupting pulse for the measurement of an E-I characteristic. The timing marks along the pulse occur at 10 microsecond intervals. Note the small current recovery during the interrupting pulse.

E-I characteristics during the recovery period were obtained by application of a 3-microsecond sampling pulse. In this case also, the E-I curve was obtained during the period of increasing anode voltage. Fig. 6 shows the main pulse with the sampling pulse to the right. The height of this pulse is indicative of the extent of recovery of the diode. Fig. 7 shows a typical E-I characteristic obtained by this method. The heavy horizontal and vertical lines are calibrating marks. Fig. 8 is a set of E-I characteristics showing the change

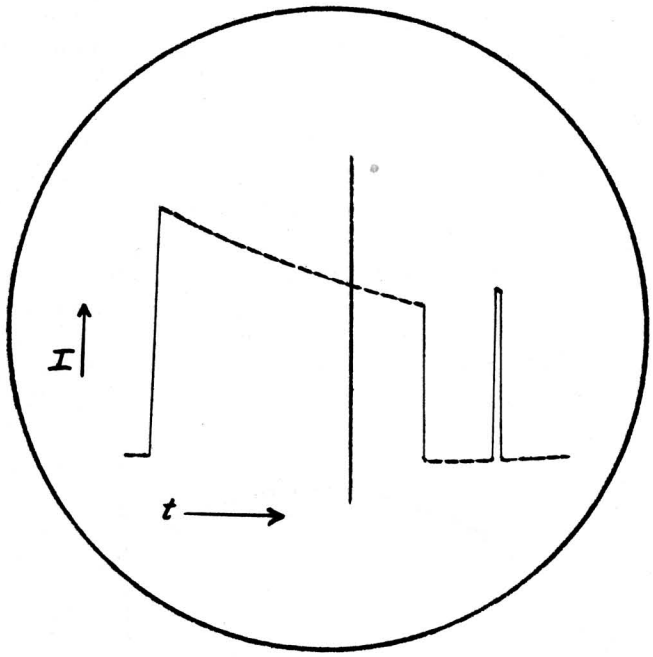


Fig. 5 – An oscillograph trace showing the current decay during a 145 microsecond pulse and a 3 microsecond sampling pulse after the main pulse to measure the recovery rate of the cathode.

occurring during the period of the pulse. Fig. 9 is a similar set of characteristics showing the change during the early part of the recovery period. In both of these sets the maximum anode voltage was adjusted to a point just less than that at which sparking near the trailing edge of the pulse occurred. The decay and recovery curve obtained from the E-I characteristics is shown in Fig. 10. Fig. 11 shows the decay and recovery cycle of another tube. The initial recovery is more rapid in the second tube. It will be noted that in both tubes there appears to be a discontinuity in the available current after the cessation of the main pulse. An examination of the main- and sampling-pulse traces in photographs, such as Fig. 6, shows that recovery starts immediately after the main pulse and that the apparent discontinuity in the plots of Fig. 9 and 10 is a result of the slow upward drift of the current (even after the tubes had been aged under full pulse conditions for 20 hours prior to the measurements) and the order in which the readings were taken. The first recovery point was read first and the last decay point was read last. Hence, the discrepancy between the decay and recovery curves is the total drift. Fig. 12 shows the data of Fig. 11 with the recovery points multiplied by the factor which matches the decay and recovery curves. This is not a proper normalization because the points are not properly weighed according to elapsed time, but it gives a reasonably accurate picture of a decay and recovery cycle.

Fig. 13 shows computed ideal planar diode characteristics. Below the field-free emission point ($I/I_o = 1$) the characteristic satisfies the 3/2 power law. It is assumed that the voltage V_o required to draw the field-free emission under space-change-limited conditions is large compared to KT/e so that initial velocities may be neglected in the current decade below the field-free emission current. Above the field-free-current point, the characteristics are Schottky curves corrected for the effects of space charge. The effect of space charge on the field strength at the cathode surface is computed by using the zero order solution for the general behavior of vacuum tubes as given by Llewellyn,[5] and solving for the field strength at the cathode surface as a function of current and applied voltage with the diode spacing as a parameter.[6]

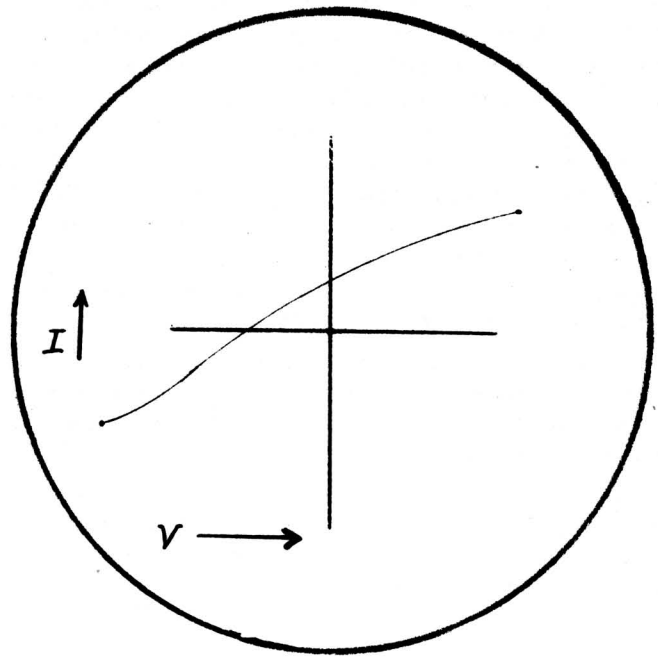


Fig. 7 – An oscillograph trace of the E-I characteristic of the test diode as measured by the 3 microsecond sampling pulse. The heavy vertical and horizontal lines are calibrating markers.

The substitution of this field strength in the Schottky formula and the subsequent

solution for the current in terms of the applied voltage and the tube parameters yields a result which is most conveniently expressed in terms of the normalized curves of Fig. 12. I/I_o is the normalized current, i.e., the ratio of the actual current to the field-free emission current. V/V_o is the normalized voltage, i.e., the ratio of the applied voltage to voltage required to obtain the field-free emission under space-change-limited conditions. γ is the parameter which embodies the remaining variables, namely, the cathode temperature and cathode-anode spacing.

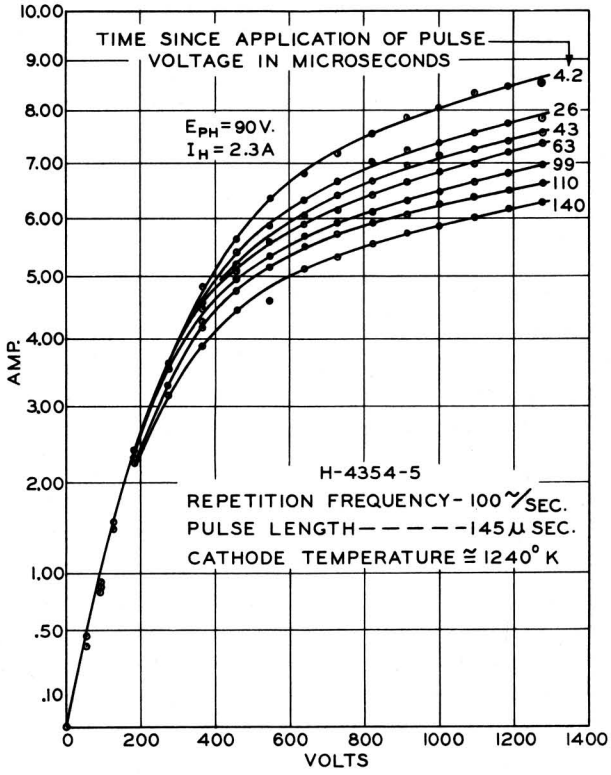


Fig. 8 – E-I characteristics during current decay. The curves are plotted on 3/2 law paper.

In principle it should be possible to superpose an experimental curve, plotted on logarithmic paper, on the theoretical curves so that the low current end of the experimental curve is asymptotic to the 3/2 law part of the theoretical curves and the high current end is asymptotic to a theoretical curve in the Schottky region. If such a fit were obtained, the field-free emission could be read from the theoretical curves and the discrepancy between the theoretical and experimental curves could be used to determine cathode impedance. Sparking

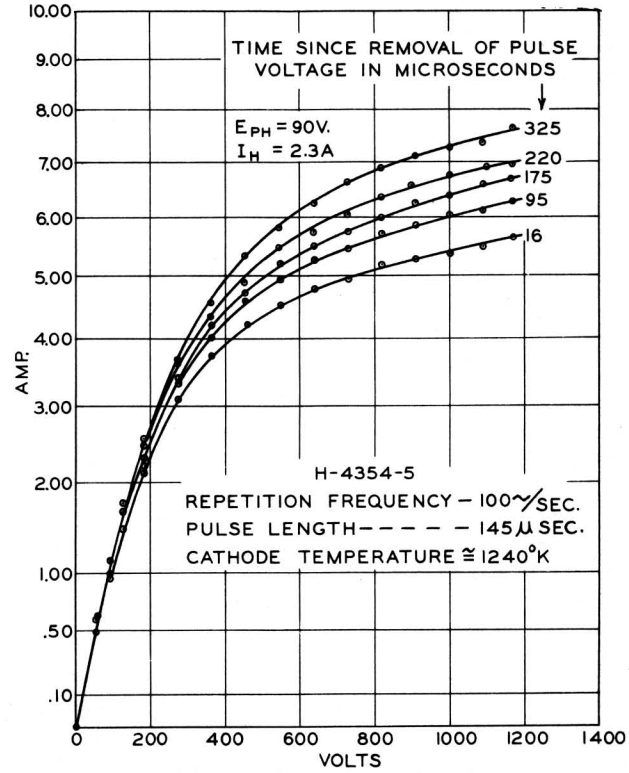


Fig. 9 – E-I characteristics during current recovery. The curves are plotted on 3/2 law paper.

limits the anode voltage to a value such that the data obtained do not extend far enough into the Schottky region to permit satisfactory comparison with the theoretical curves. The best fits obtainable with the present data indicate that the temperature of the cathode falls during the pulse. The rises of temperature observed with the cathode thermocouples make a

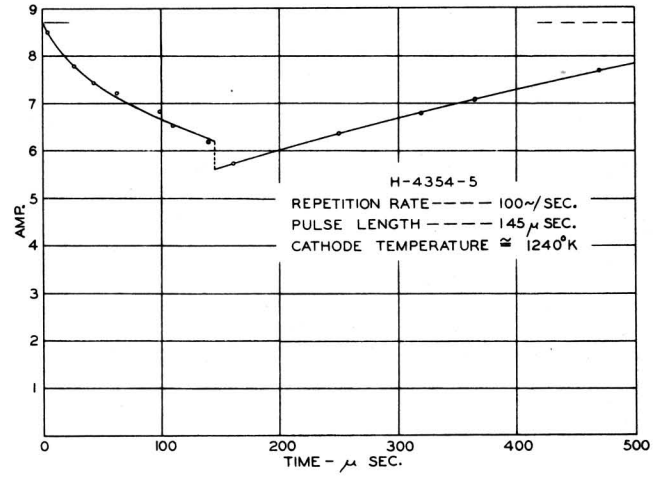


Fig. 10 – The decay and recovery of the anode current of diode H-4354-5, plotted points are the 1200 volt points of the E-I characteristics of Figs. 8 and 9.

temperature fall during a pulse seem most improbable. The observation that the cathode temperature does rise and the departure of the experimental curves from the 3/2 law at very modest current densities makes it quite clear that oxide or interface resistance is playing a substantial role. If it is assumed that the deviations from the space charge line are due to a non-linear resistance in coating or interface, the power density at the sparking point agrees quite well with values obtained in the same way by Eisenstein and others.[7] It appears that sparking, a consequence of cathode resistance, makes the determination of the cathode resistance impractical by the curve matching method.

All of the curves of Figs. 8 and 9 appear to have the same shape. This is borne out in Fig. 14 in which the curves of Figs. 8 and 9 have been normalized to the peak current at the beginning of the pulse (↑). The spread in points is indicated at 200-volt intervals. In the high-voltage region where departures from the 3/2 law are greatest and where the curves might be expected to differ most, the curves become identical within the experimental accuracy. It should be noted that this region also has the highest experimental accuracy. That this behavior is not characteristic of simple emission decay can be seen from the following argument: As the field-free emission of a cathode falls, V_o of Fig. 13 falls as the 2/3 power of the emission current, γ decreases as the 1/3 power of the emission current, and the characteristic flattens towards the voltage axis. This flattening is not observed in the experimental curves. While Fig. 14 sheds no new light on the mechanism responsible for decay, it supports the previous conclusion that the interior of the cathode plays a significant role in the decay process.

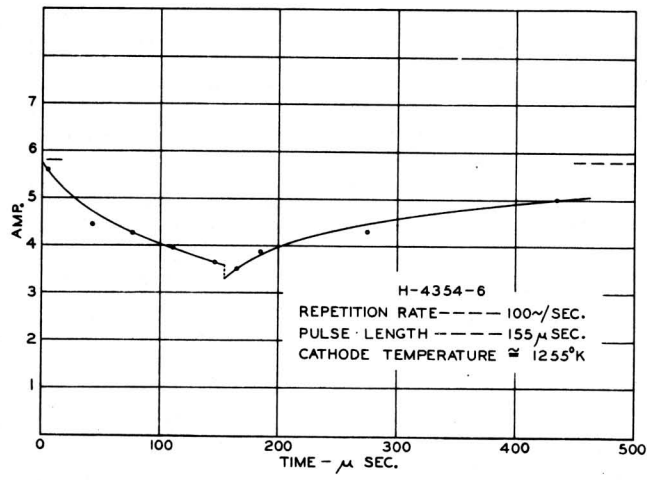


Fig. 11 – The decay and recovery of the anode current of diode H-4354-6.

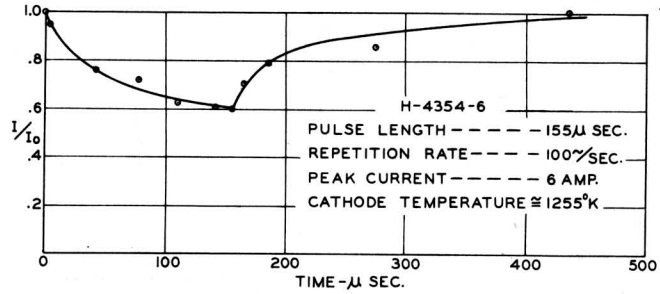


Fig. 12 – Decay and recovery currents of diode H-4354-6, normalized to the initial pulse current.

Conclusions

Although the principal object, to locate definitely the source or sources of decay, has not been achieved, a large body of pertinent data has been accumulated. Any satisfactory theory of decay must explain these data.

While the present data do not definitely locate the source of the decay, they do indicate that some possible sources are improbable. If the anode is assumed to be the source of decay, then it is difficult to explain the fact that sparking observed here and elsewhere can be correlated with definite power densities in the cathode despite widely varying tube geometries. If gas poisoning is assumed to be the source, a suitable mechanism must be devised. If any likely collision cross-section for ionization is chosen for the residual gas in the cathode-anode space, then a simple calculation shows that, for any reasonable pressure, all the gas in this space will arrive at the cathode in a very small fraction of the time involved in the observed decays. If decay is assumed to be due to a change in the field-free emission of the cathode, then it would be expected that sparking could be correlated with the field strength at either the cathode or the anode. Such a correlation has not been observed in these experiments. Furthermore, the fact that the shape of the E-I characteristics remains substantially invariant during decay is

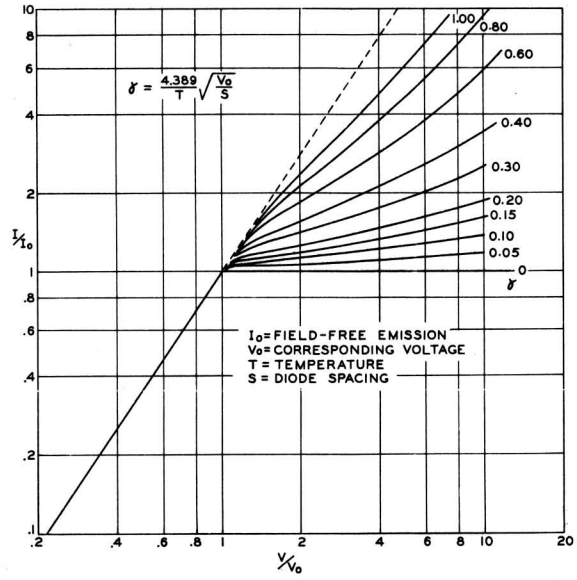


Fig. 13 - Theoretical E-I characteristics for a planar diode with the Schottky characteristics corrected for the effect of space charge on the field at the cathode.

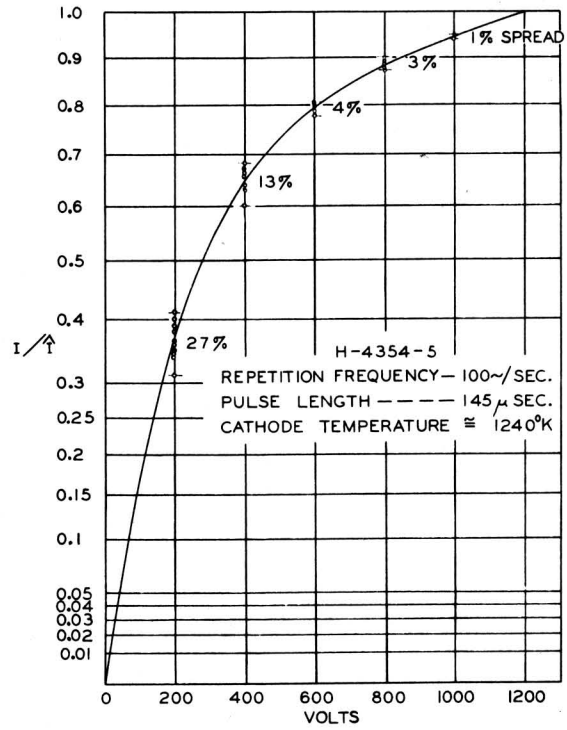


Fig. 14 - Decay and recovery E-I characteristics normalized to the initial current.

difficult to reconcile with an emission limitation. Other possible sources of decay are coating and interface resistances. The present investigation has produced no data which are inconsistent with the assumption that decay and sparking are caused by internal cathode impedance.

Further measurements are planned to distinguish between changes of internal cathode impedance and other sources of decay. Several approaches are being investigated. (1) Measurements of anode power dissipation and cathode temperature rise would, in theory, make the necessary distinction. The energy input to a diode during a pulse is the product of the charge content of the current pulse and the applied voltage. If the voltage drop through the cathode is trivial, all of the energy will be dissipated at the anode. On the other hand, if the voltage drop through the cathode is substantial, part of the energy input is dissipated in the cathode, the cathode temperature rises and the anode dissipation decreases. A measurement of cathode temperature rise or a measurement of anode dissipation, as a function of pulse length, would separate emission decay from a change of cathode resistance. However, the practical difficulties involved, such as measuring a small change in the already large anode dissipation, make this method unattractive. (2) Measurements of the surface potential of the cathode throughout the pulse, although difficult, appear the most promising. Possible methods of determining this potential are: (a) by passing a beam of charged particles through the cathode-anode space parallel to the surface of the cathode and observing the change in their velocity; (b) by measurement in a retarding field of the velocity of electrons passing through a hole in the anode, and (c) by measurement of the potential of an emitting probe placed close to the cathode surface.

It is essential to complete any of these measurements in a time small compared with the period of the decay in order to establish that the decay is entirely due to changes within the cathode. This requirement complicates the measurement problem. None of the methods so far considered is amenable to detailed analysis and further experiments will probably be necessary to select a suitable method.

R. M. Matheson

R. M. Matheson

Leon S. Nergaard

Leon S. Nergaard

References

[1]H. Y. Fan, *J. Appl. Phys.*, 14, 552–560 (1943).

[2]Cited by A. Eisenstein in ADVANCES IN ELECTRONICS, Vol. 1, Academic Press, 1948.

[3]R. L. Sproull, *Phys. Rev.*, 67, 166–178 (1945).

[4]C. E. Haller, *Electronics*, 126–130 and 354–356, July (1944).

[5]F. B. Llewellyn, *Proc. IRE*, 21, 1532–1573 (1933).

[6]A similar computation of the field at the cathode has been made by H. F. Ivey, *Phys. Rev.*. 76, 554 (1949).

[7]A. Eisenstein, *J. Appl. Phys.*, 20, 776–790 (1949).