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On the Cause of the Anomalous Flicker Effect*

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This paper extends earlier work by Johnson and Donal on the anomalous flicker effect, observed in tubes with a tungsten cathode under space-charge limited condition, and attributed to positive ions emitted by the cathode. This extension involves the observation of the individual current pulses causing the effect and the measurement of the flicker effect noise spectrum over a wide frequency range. The results indicate that these pulses are due to sudden bursts of about $10^6$ positive ions emitted by the cathode in less than 1 μsec and trapped in the space charge for many μsec. The trapping time of the ions is determined from the shape of the pulses and from the noise spectrum, and the results are found to agree. An experiment that verifies directly that the effect is caused by positive ions also shows the way to eliminate the effect. A discussion of the nature of these sudden bursts is offered and various mechanisms for the observed decay of the pulses are presented.

1. INTRODUCTION

If a vacuum tube having a tungsten filamentary type cathode is operated under space-charge limited condition and used as the first stage of a high-gain amplifier, an oscillogram of the output voltage shows a number of large, unidirectional pulses superimposed on the normal shot noise spectrum. These pulses give rise to a noise spectrum that is flat at low frequencies and decreases sharply at higher frequencies. The effect is known as the anomalous flicker effect and was discovered by Johnson in 1925.

Johnson suggested that the pulses were caused by clusters of ions which passed directly through the potential minimum, thus giving rise to current pulses equivalent to the passage of $10^9 - 10^{10}$ electrons, and calculated that these clusters might contain $1.7 \times 10^5$ singly charged tungsten ions.

Donal found that in tubes with an oxygen pressure of 3.75×10^{-3} mm of mercury an effect was caused by ions of WO_2 and WO_3. He considered the trapping of single ions in the potential minimum and was able to determine a trapping time varying from 31 μsec to 213 μsec depending upon the tube operating conditions. Since his measurements were carried out at the high-frequency end of the spectrum, the above values of the trapping time are not the result of direct observation, but involve several theoretical assumptions.

This paper will present results which indicate that the effect is caused by groups of positive ions which are emitted almost simultaneously and are subsequently trapped in the potential minimum. These conclusions follow from a direct observation of the size and shape of the individual current pulses with a cathode ray oscillograph and from measuring the noise spectrum, caused by these pulses, over a wide frequency range. It is thus possible to determine the trapping time of the ions by two independent methods.

Most of the tubes used in the following experiments were Sylvania 5722 noise diodes. The tubes used in the noise reduction experiments were built in the tube laboratory of the Electrical Engineering Department of the University of Minnesota.

In all cases the noise was measured in terms of the equivalent saturated diode current at the output of the tube as defined by Schottky's theorem

$$\langle i^2 \rangle_n = 2ei \Delta f.$$ 

The noise was measured on the multi-channel noise spectrum analyzer by the methods described by Nielsen and van der Ziel.  

2. OBSERVATION OF THE INDIVIDUAL CURRENT PULSES

Observation of the individual current pulses at a slow sweep speed (5 msec/cm) indicated that about $10^6 - 10^7$ pulses occurred per sec; this is illustrated in Fig. 1. The number of pulses per sec was not strongly dependent upon the current, but it increased strongly with increasing cathode temperature. The size and shape of the individual pulses depended upon the current, however. By using a very high sweep speed (0.2 μsec/cm), the initial stages of the current pulses could be observed. Figure 2(a) indicates a rise time of about 0.2 μsec and an interesting periodic structure with a period of about 0.6 μsec that is not always as well pronounced as shown here. Observations at a somewhat

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lower sweep speed (5 μsec/cm) show [Fig. 2(b)] that this sharp rise is followed by a slow exponential decay. For a pulse starting at \( t = t_0 \) the pulse shape can be represented approximately by the equation

\[
I(t) = \begin{cases} 
0 & \text{for } t < t_0 \\
A \exp[-(t-t_0)/\tau_0] & \text{for } t > t_0.
\end{cases}
\]

All pulses had roughly the same value of \( \tau_0 \); the value of \( \tau_0 \) is usually of the order of many μsec and depends upon the operating conditions. The peak value of the pulses shown in Fig. 2 corresponds to a current of the order of a few μA.

The polarity of the current pulses corresponds to a current increase; this indicates that the effect must be caused by positive ions, as was already deduced by the earlier investigators. The number of electrons liberated by a singly charged ion trapped in the space charge cloud for a time \( \tau_0 \) is of the order of \( \tau_0/\tau_e \) where \( \tau_e \) is the transit time of the electrons; substituting \( \tau_0 \approx 10^{-5} \) sec and \( \tau_e \approx 10^{-9} \) sec yields a value of about \( 10^4 \) electrons per ion. A similar estimate follows from Thompson and North’s theory of collision ionization noise. The periodic structure of the beginning of the pulse indicates that the positive ions at first oscillate almost synchronously around the potential minimum; the maxima in the current correspond to the passage through the potential minimum and the minima correspond to the largest deviation from the potential minimum. The observed period \( \left( \approx 0.6, \mu\text{sec} \right) \) corresponds roughly to what one would expect for the period of such an oscillation. The fact that the synchronism is lost after a few oscillations must be attributed to the spread in initial velocity (both in magnitude and direction) of the individual ions. The rapid rise time and the periodic structure indicate that the ions must be released within a very short time interval, probably only a few tenths of a μsec. The observed decay time indicates that the individual ions make many oscillations around the potential minimum before they are taken out of circulation.

### 3. NOISE MEASUREMENTS

The foregoing results were substantiated by noise measurements. A typical noise spectrum is shown in Fig. 3. It was found that the spectrum could be represented by the equation

\[
\langle \bar{v}^2 \rangle_n = 2eT_1 \int_0^\infty f \frac{\text{const} df}{1 + \omega^2 \tau_1^2}.
\]

where the time constant \( \tau_1 \) depended strongly upon operating conditions; \( \tau_1 \) could be determined by measuring the spectrum over a wide frequency range. Donal measured only the noise for \( \omega \tau_1 \gg 1 \).
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Fig. 4. Anomalous flicker noise spectra of a 5722 noise diode at a filament voltage of 4 v for various plate currents, indicating the absence of anomalous flicker effect at low currents and close to saturation as well as the dependence of the lifetime of the ions upon operating conditions.

It was found that the time constant $\tau_1$ determined from the noise spectrum [Eq. (2)] and the time constant $\tau_0$ determined from the shape of the individual current pulses [Eq. (1)] agreed within the limit of accuracy. This is understandable from a Fourier analysis of the current pulses. If individual current pulses of the form (1) occur at random at the average rate $N_0$, then the noise spectrum can be shown to be

$$
\langle \vec{f}^2 \rangle_{\text{nu}} = \frac{2A^2N_0\tau_0^2}{1+\omega^2\tau_0^2} df.
$$

(3)

This assumes that all current pulses have the same initial height $A$. If the height of the individual current pulses fluctuates, one obtains instead of (3):

$$
\langle \vec{f}^2 \rangle_{\text{nu}} = \frac{2\langle f^2 \rangle_{\text{nu}}N_0\tau_0^2}{1+\omega^2\tau_0^2} df,
$$

(3a)

which is of the form (2) with $\tau_1=\tau_0$, so that $\tau_1$ indeed corresponds to the average trapping time. Substitution of the observed values for $A$ and $\tau_0$ yields $N_0=10^5$ to $10^6$ pulses/sec, which agrees with direct observations.

It is thus possible to determine the value of $\tau_0$ also by fitting the experimental noise spectrum to a theoretical curve of the type (3). This has been done for a number of experimental spectra of the type shown in Fig. 4. We found that the value of $\tau_0$ depended strongly upon operating conditions. At an emission current of 3-4 ma, a distinct maximum value of $\tau_0$ of about 30 $\mu$sec occurred at a plate current of 1 ma; at that plate current the value of $\langle \vec{f}^2 \rangle_{\text{nu}}$ was also a maximum.

The anomalous flicker effect became negligible at very low plate currents where the anode voltage was negative; this is understandable since the ions can be captured by the anode in that case and do not remain trapped in the space charge for a long time. The effect also became negligible at plate currents slightly below the saturated emission current; this is understandable, since the potential minimum is then very close to the cathode so that the ions do not remain trapped in the space charge for a long time. These observations helped in finding a method for eliminating the effect. (See Sec. 4, following.)

Some aging experiments were performed to determine the type of ion involved in the process; the results are shown in Fig. 5. These curves indicate that short-time, high-temperature flashing has little influence on the effect but that longer-time, lower-temperature aging reduces the effect considerably. These results seem to rule out surface impurity ions as a contributing factor but do not distinguish among deep-lying impurities, tungsten ions, or oxides of tungsten as causes of the effect.

Fig. 5. Anomalous flicker noise spectrum of a 5722 noise diode at a plate current of 1 ma and a filament voltage of 4 v for a new tube, for the same tube after flashing, and for the same tube after 40 hr of aging, showing the decrease in anomalous flicker noise during aging.

4. DIRECT DETERMINATION OF THE SIGN OF THE ION CHARGE

Though it has been known for a long time that the anomalous flicker effect is caused by positive ions, it seems worth while to mention an experiment that proves this in a very direct manner, especially since it also indicates how the effect can be eliminated.

In these experiments an "ion sink," consisting of a
solid metal shield at zero or negative potential, was placed very near to the tungsten filament of a diode, in the manner shown in Fig. 6. When maintained at cathode potential or when made negative with respect to the cathode the sink should pick up the positive ions so that they are not trapped in the space charge. That this actually happens can be seen from Fig. 7; here \( V_a \) is the anode voltage, \( V_s \) the voltage of the ion sink and \( V_c \) the cathode voltage. With \( V_a = V_s \), the tube acts as a normal diode and anomalous flicker effect is present. However, at \( V_a = V_c \) and \( V_a = V_c - 6 \) v the effect has been reduced to the point where it is unnoticeable. The same type of construction has been used in a tungsten triode by winding a grid across the open end of the shield. For this tube the results were similar to those of Fig. 7.

5. DISCUSSION OF THE RESULTS

The question where these bursts of ions come from still has to be answered. The most likely explanation is that they are the result of small pockets of impurities (e.g., concentrated at grain boundaries or other lattice imperfections). Normally these pockets are bottled up and few ions, if any, escape; moreover, since they would escape as individual ions, they would not produce a measurable effect. Only if a pocket is suddenly opened as a result of tungsten evaporation, would one expect a big enough burst of ions to produce a noticeable effect. The decrease in anomalous flicker effect during aging would then indicate the gradual decrease in the number of surface pockets that are not yet open. One might expect an exponential decrease in the number of closed pockets with time.

Such a mechanism does not seem unlikely, for it is known that many impurities, such as, e.g., alkali atoms and tungsten oxide molecules, will evaporate as positive ions. Furthermore, in view of the high temperature at which the cathode operates, an escape time less than 1 \( \mu \text{sec} \) is not impossible.

Fig. 6. Diode with a tungsten filamentary cathode and incorporating a nickel shield that can be used as an ion sink by biasing it negatively.

The following mechanisms might be responsible for the observed decay times of the individual pulses:

(a) The ions may be neutralized by picking up electrons.
(b) The ions are captured by the cathode.
(c) The ions are captured by the anode.
(d) The ions gradually drift out of the system.

We cannot completely discriminate between these possibilities. The results of Sec. 4 show that (c) is an important mechanism if the anode is at zero or negative potential. Mechanism (b) seems unlikely, for the suddenness of the bursts of ions requires a short sticking time of the ions at the cathode. Mechanism (a) gives a possible explanation of the dependence of the trapping time upon operating conditions.

6. CONCLUSIONS

The foregoing experiments indicate that the anomalous flicker effect is caused by sudden bursts of positive ions emitted by the cathode within a time interval much less than 1 \( \mu \text{sec} \) and trapped in the space charge for many \( \mu \text{sec} \). The trapping time of the ions can be determined from direct observation of the current pulses associated with the effect and from noise measurements; the results are in good agreement. About \( 10^6 \) ions are released in a single burst. An explanation for the occurrence of these bursts is offered and several mechanisms responsible for the decay of the ion bursts are presented; it is at present impossible to discriminate completely between these mechanisms.

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