On the Initial Decay on Thermionic Emission from Oxide-Coated Cathodes

On the Initial Decay of Thermionic Emission from Oxide-Coated Cathodes*

Kazuo ISHIKAWA

Research Institute for Scientific Measurements

(Received August 13, 1956)

Synopsis

Using ordinary diodes and also diodes having a getter chamber, the initial decay of thermionic emission from oxide-coated cathodes over about 0.1 second was observed on the conditions of various cathode temperatures and also various anode voltages, and the change of initial decay was examined by keeping a cathode at high temperature and also by heating or cooling a getter deposit. As a result, it was found that by heat treatment of cathode at high temperature in the ordinary diode the initial decay of saturation current at observation temperature became slower than that before the treatment, that the decay characteristic could be restored to that before the treatment by applying high anode voltage and drawing out emission current, and that these phenomena similarly occurred also in the case of heating a getter deposit in both tubes. Also an initial decay of emission current more rapid than the initial decay of saturation current was found to occur at low anode voltages. In order to explain the above-mentioned phenomena, the poisoning of cathode due to residual gases was considered as the main cause of initial decay of saturation current, while the drop of anode potential caused by charging up of contamination on the anode was considered as the main cause of initial decay of emission current at low anode voltage.

I. Introduction

Since J. P. Blewett[1] performed a systematic study on the initial decay of saturated thermionic emission from oxide-coated cathodes, many workers have investigated this phenomenon over various time ranges, and proposed various explanations for its mechanism. Blewett explained the decay over several minutes on a theory that free barium ions existing near the thermionic emitting surface of an oxide coating would migrate towards the base metal on account of the applied electric field. Then, R. L. Sproull[2] proposed a theory of decay in which the above-mentioned mechanism could be applied to an atomic layer of barium existing on the emitting surface of coating, and which would explain the rapid decay during 100μ sec order. H. Kawamura and A. Sinohara[3] considered the cause for the decay over about 0.01 sec was to be found in the cooling effect of the thermionic emission surface due to evaporation of electrons. E. A. Coomes[4] suggested that rapid decay would occur in a transitional state because, at resting state, the conduction band of an oxide emitter contained more electrons than those in working

* The outline of this paper was reported in J. Appl. Phys., **22** (1951), 986 by T. Hibi and K. Ishikawa.

(1) J. P. Blewett, Phys. Rev., **55** (1939), 713.
(2) R. L. Sproull, Phys. Rev., **67** (1945), 166.
(3) H. Kawamura and A. Sinohara, Tôshibaken., **18** (1943), 301 (in Japanese).
(4) E. A. Coomes, J. Appl. Phys., **17** (1946), 647.

state. All of the above-mentioned mechanisms are based on a view that the initial decay is a proper phenomenon in the oxide-coated cathodes. On the contrary, G. R. Feaster[5] studied experimental tubes with an intentionally contaminated anode, and showed that poisoning action of gases might be the cause of the decay during about 10μ sec pulse. Recently, K. Amakasu and T. Imai[6] found that the evolution of oxygen by electron bombardment from the contaminated anode might be the main cause of the decay over several minutes.

In spite of the fact that many investigations have been performed on the initial decay of oxide-coated cathodes and its mechanism has been discussed, as mentioned above, the true cause has not yet been found. In the present study, to confirm this point, the initial decay over about 0.1 sec was observed at various cathode temperatures and anode voltages, and the effects of keeping a cathode at high temperature and of heating or cooling a getter deposit were also examined systematically.

II. Specimen and apparatus

In order to study the initial decay, experimental tubes of two types, a- and b-types, were used. As shown in Fig. 1(a), the tube of a-type is an ordinary diode with guard cylinders which is used for observing the emission characteristic. The base of the cathode was an electrolytic nickel sleeve of indirectly heated type about 1.7 mm in diameter and about 35 mm in length, on which equimolar mixture

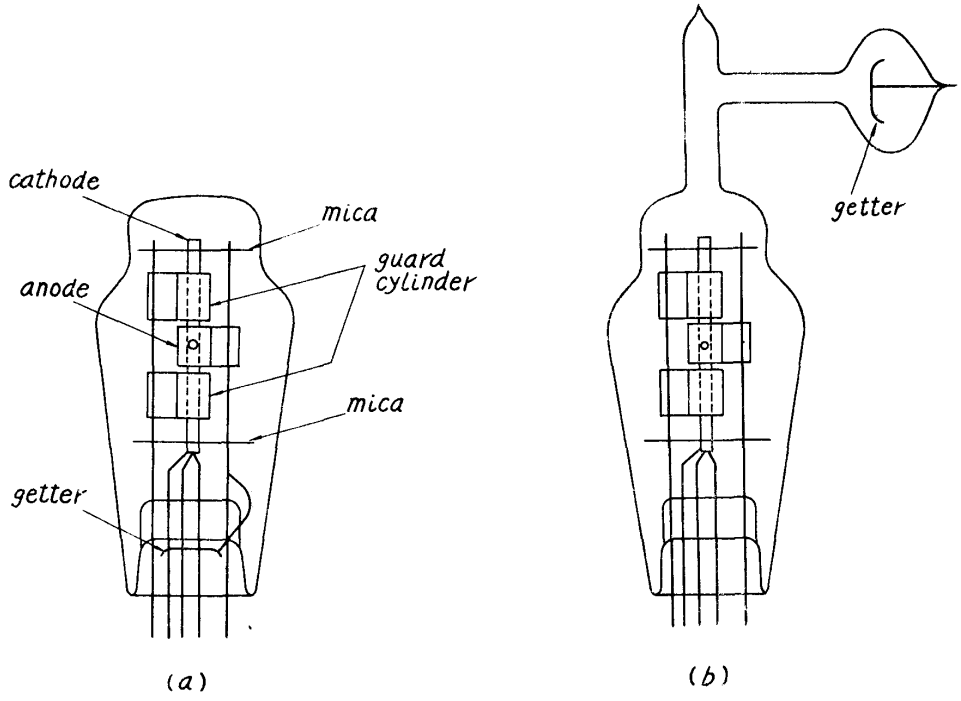

Fig. 1. Experimental tubes.

(5) G. R. Feaster, J. Appl. Phys., **20** (1949), 415.
(6) K. Amakasu and T. Imai, J. Appl. Phys., **24** (1953), 107.

of barium and strontium carbonates was sprayed. After this coating was decomposed into (BaSr)O by heating up to about 1,270°K and the tube was sealed off, the cathode was activated by drawing out the emission current at a temperature below 1,270°K. The anode was a cylinder of nickel about 6 mm in diameter and about 7 mm in length. Two guard cylinders having the same diameter as the anode were mounted respectively at the positions about 1 mm above and below the anode. On the lower part of the glass wall of the tube, a barium getter is deposited. In tubes of b-type, as shown in Fig. 1(b), a barium getter is deposited on the glass wall of a separate chamber which is connected through a side tube to the main bulb having an electrode system similar to the a-type.

To observe the initial decay, a Braun-tube oscillograph was used. Voltage drop, which was caused by the emission current between the both ends of a resistor of 0.5~2,000 ohms, was amplified and led to the phenomenal axis of the Braun-tube. A single-sweep time axis utilizing the discharge of electric condenser was used. Time scale t', therefore, has a relation $t' = 1-\exp(-t/\tau)$ to time t, if the total length of the time axis is assumed as unity, where τ is a time constant. In the present experiment, τ was taken to be 0.1 sec. All of the decay characteristics shown in the following figures are represented by using this time scale. The phenomena appearing on the screen of Braun-tube were observed or photographed. Temperature of a cathode was measured by using an optical pyrometer through a small opening bored in an anode cylinder, but no correction was made by the emissivity. To heat the getter deposit from outside of an experimental tube, the part of glass wall having a getter deposit was heated by radiation from an electric heater in the case of a-type tube and by a small electric furnace surrounding a getter chamber in the case of b-type tube. Temperature of the getter deposit was measured by using a mercury thermometer, in which the mercury part was contacted to the outer surface of the glass wall having the getter deposit. The values give, therefore, only an approximate measure of its temperature.

III. Experimental results

1. Dependence of initial decay characteristic on cathode temperature and anode voltage

It was observed that the initial decay characteristic in a-type tube generally depended on the cathode temperature and anode voltage, as shown in Fig. 2. In this figure, the dependence of the decay characteristic on the cathode temperature at a fixed anode voltage is shown horizontally, and that on the anode voltage at a fixed cathode temperature vertically. For the comparison of the form of the characteristics only, the initial values of the emission current in ordinate are arranged as of uniform height by adjusting the scale. It is seen from this figure that the initial decay characteristic changes regularly with changes in the cathode temperature and anode voltage as follows:

(1) Diagram of the initial decay with changes in temperature and voltage is divided into four regions A, B, C, and D, according to the decay form.

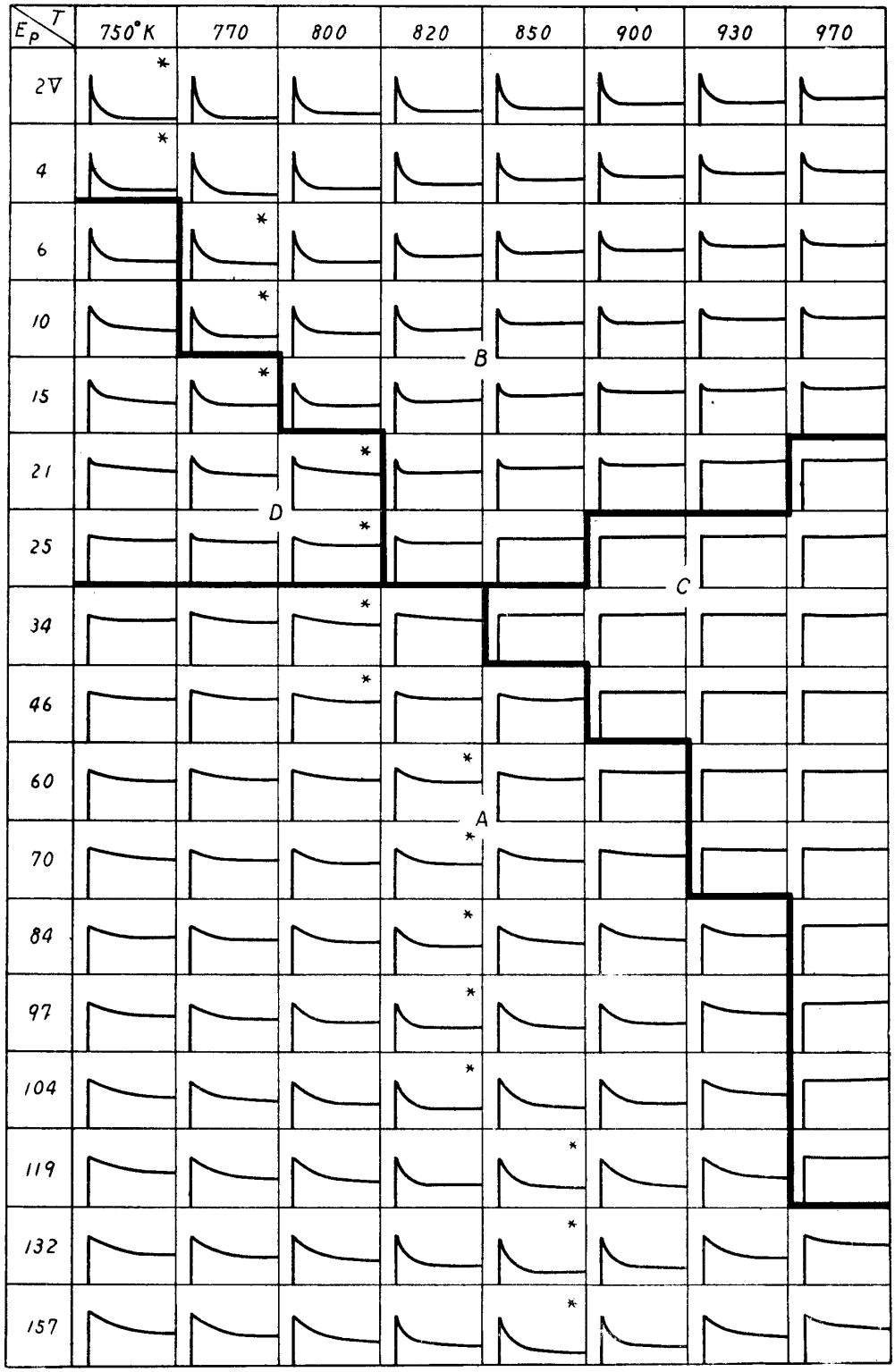

Fig. 2. Dependence of initial decay on cathode temperature and anode voltage (a-type tube). Initial values are arranged as of uniform height.

(2) The region A is one where the decay of saturation current appears which has been hitherto studied by many workers. This decay becomes remarkable with increase of the anode voltage at a fixed cathode temperature.

(3) The region B exists in anode voltages lower than that in region A. The decay in this region is in general more rapid than that of saturation current and, in contrast to the latter, becomes less marked with increasing anode voltage at a fixed cathode temperature. Such a decay will be called "low-voltage decay" hereafter. The decay characteristic was observed in seven tubes at anode voltages higher than 2 V: No low-voltage decay was observed at all in two tubes and in one tube, it disappeared entirely with the progress of activation though it was observed slightly in lower activation stage. And in the case of tubes which showed a marked low-voltage decay, the decay became less remarkable with the progress of activation. Since the boundaries between each region shown in this figure transfer with different tubes or even on the same tube with activation, as mentioned above, they have only qualitative meanings.

(4) In the region C the decay does not occur, and this region extends to higher and lower anode voltage sides with increasing cathode temperature.

(5) In the region D, the decay of saturation current appears together with the low-voltage decay.

(6) As shown by asterisk in the figure, there exists a cathode temperature for every anode voltage, where the decay is most pronounced and such a cathode temperature transfers to higher temperature side with increasing anode voltage.

2. Initial decay of saturated emission current

(i) Effects of high-temperature heating of cathode

Using a-type tubes, the effects of the heat-treatment of the cathode on the decay characteristic were studied systematically, by observing the characteristic at a definite observation temperature after the cathode had been kept for some time at a temperature considerably higher than the observation temperature (such a heat-treatment of cathode will hereafter be called "high-temperature heating of cathode").

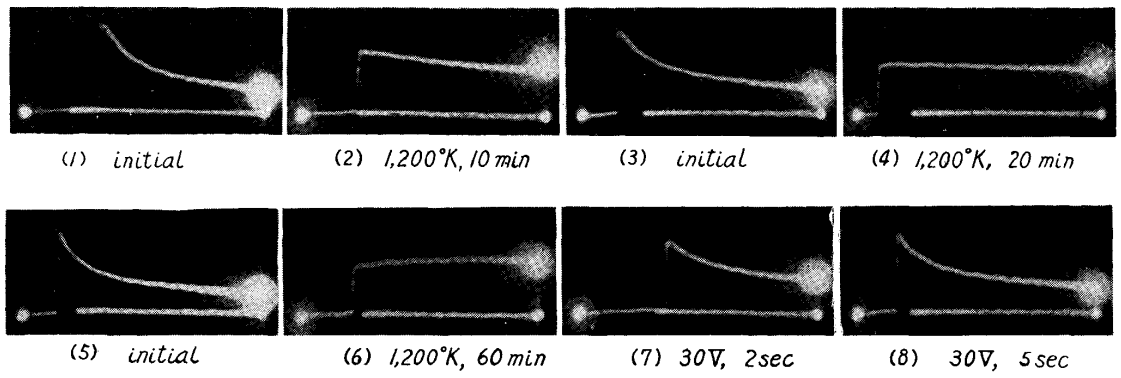

Fig. 3. Change of decay characteristic by high-temperature heat treatment of cathode, and recovery process of decay characteristic (a-type tube). Observation at T = 850°K and E_p = 30V.

An example is shown in Fig. 3. Initially the decay characteristic was such as shown in (1) at a cathode temperature 850°K and anode voltage 30 V. After heating a cathode at 1,200°K for 10 min, the initial value decreased and the final value increased, and the decay diminished as shown in (2). The initial characteristic such as shown in (3) at 850°K and 30 V became like (4) after heating the cathode at 1,200°K for 20 min, and the initial characteristic such as shown in (5) at 850°K and 30 V became like (6) after heating the cathode at 1,200°K for 60 min. This shows that the effect of heat treatment becomes more pronounced with prolongation of the heating period. In this case, no notable differences were observed on the characteristic after treatment between the case where the cathode was cooled from the treatment temperature to the observation one by score of seconds and the case by score of minutes. As a result of drawing out emission current for about 2 sec by applying 30 V to the anode in the state of (6) where the decay disappeared with high-temperature heating of the cathode, the characteristic became like (7) and the decay appeared again. By further application of the anode voltage for about 5 sec the decay became more pronounced like that in (8), and we could obtain the characteristic similar to (5) which appeared before high-temperature heating of the cathode. In this manner, the state induced by high-temperature heating of the cathode can be restored almost to the initial state, if an emission current is drawn out by applying a fairly high anode voltage of score of volts. A systematic study can be performed, therefore, by restoring to approximately uniform initial state after heat treatment of cathode. In the following experiments, the initial characteristics were always arranged uniformly.

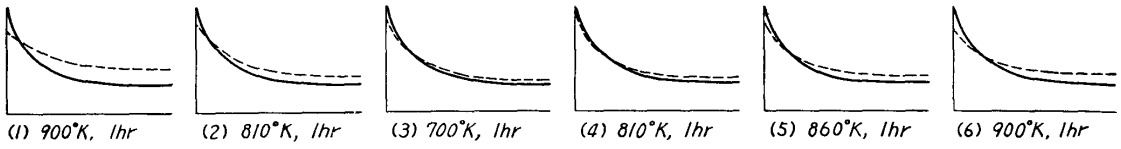

Fig. 4. Dependence of decay characteristic on heat treatment of cathode at various temperatures (a-type tube). Solid and dotted curves represent characteristics before and after heating respectively. Observation at $T = 810$°K and $E_p = 80$V.

Fig. 4 shows the dependence of the decay characteristic of a-type tube on heat treatment of the cathode at various temperatures. In the figure, (1), (2),..... represent the order of observation, and the values of temperature and time show the condition of heating the cathode. In this case, the period of heat treatment was always 1 hr. The solid curves represent the characteristic before heating and the dotted curves after it. (Also in the figures hereafter, the order of observation, the condition of treatment, and the decay characteristics before and after treatment will be represented in this manner.) The temperature of observation was always 810°K and the anode voltage 80 V. From a comparison between (1), (2), and (3) and between (4), (5), and (6) in this figure, it is seen that the higher the temperature of heating the cathode is, the slower the decay becomes after

heating. Also a comparison between (2) and (4) and between (1) and (6) shows that the change becomes less by repetition of the heating.

By using a-type tube, a comparative experiment was performed between the case where only the high-temperature heating of the cathode was carried out and the case where the emission current was drawn out by applying a low anode voltage simultaneously with the former treatment. The results are shown in Fig. 5.

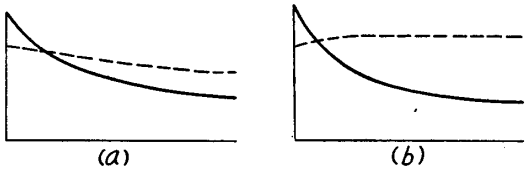

Fig. 5. Comparison between two decay characteristics in the cases of high-temperature heat treatment of cathode (a), and simultaneously with the treatment (a), applying low anode voltage (b) (a-type tube). Solid and dotted curves represent characteristics before and after treatment respectively. Observation at $T = 850°K$ and $E_p = 30$ V.

In this figure, (a) shows the changes in the decay characteristic by heating the cathode at 1,200°K for 15 min, and (b) shows the changes in it when the emission current was drawn out by applying about 2 V on the anode at a cathode temperature of 1,200°K for 15 min. In both cases observations were made at a cathode temperature of 850°K and an anode voltage of 30 V. It is seen from this figure that in the case of applying low anode voltage in heating the cathode, the increase in the final value becomes more pronounced, as compared with the case of only high-temperature heating of cathode, though the decrease in the initial value is almost equal. There is, however, an upper limit for the application of voltage, and if too high voltage is applied the decay becomes more remarkable than the case where only temperature heating is applied.

The above-mentioned recovery phenomenon caused by applying the anode voltage was observed at 810°K and 80 V for a-type tube, varying the anode voltage applied for the recovery after heating the cathode at 1,000°K for 10 min. The result is shown in Fig. 6. The curves represent changes in the initial values in the case where various anode voltages were applied. The changes in the final value are omitted in this figure because they are similar to those in the initial value and because they are small in amount. As seen from the figure, if the cathode is kept at the observation temperature after high-temperature heating of the cathode, the emission current decreases slightly (curve 0 V). If a low anode voltage is applied, the emission becomes almost unchanged (curve 4 V). With further increase of the anode voltage, the emission increases, and then decreases through a maximun (curves of voltages higher than 6.5 V). In this case, with increase of applied voltage, the peak in these recovery curves becomes higher and sharper and appears earlier. On the contrary, at voltages higher than certain values (13~16.5 V), the peak intensity decreases, though the peak becomes still sharper and appears still earlier than in the case of lower voltages. Therefore,

in order to restore the cathode to the initial state, one should cease applying the anode voltage soon after the initial and final values become equal to those of the initial stage of the cathode.

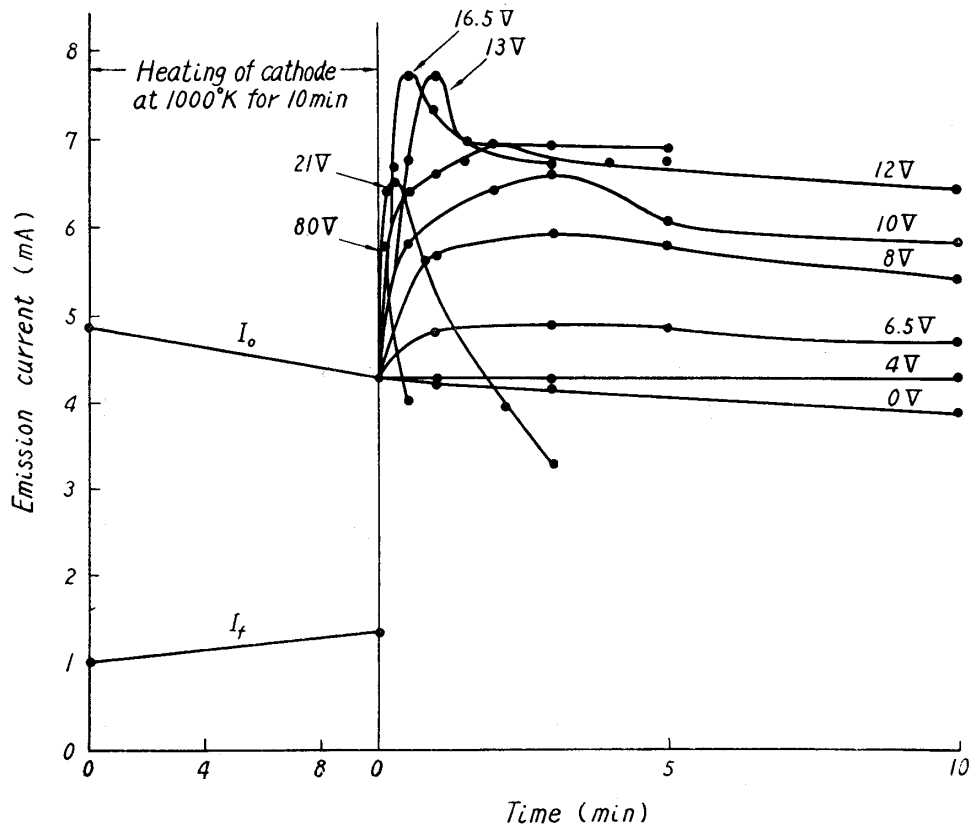

Fig. 6. Behaviour of recovery of initial value by applying various anode voltages (a-type tube). I_0: initial value, I_f: final value. Observation at $T = 810°K$ and $E_p = 80V$.

(ii) Experiments by heating or cooling a getter deposit

(a) Using tubes of a-type, the change in the decay characteristic was examined, by heating from outside of the tube a part of the glass wall where the getter was deposited, leaving the cathode at room temperature (Fig. 7). In this figure, the values of temperature and time represent the condition of heating the getter deposit. In this case, the period of heating was all 1 hr. The temperature of observation was always 810°K and the anode voltage 80 V. It is seen from the comparison between (1), (2), and (3) in the figure that by heating a getter deposit

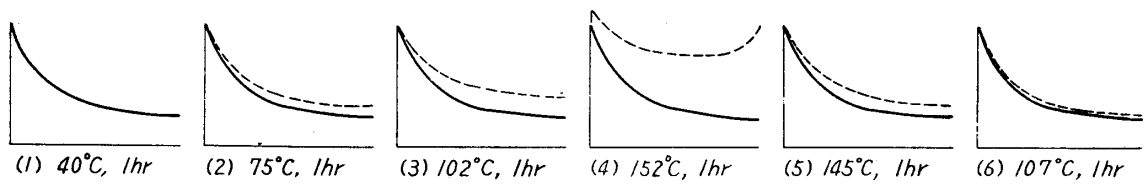

Fig. 7. Change of decay characteristic by heating a getter deposit at various temperatures (a-type tube). Solid and dotted curves represent characteristics before and after heating respectively. Observation at $T = 810°K$ and $E_p = 80V$.

the final value increases and the decay becomes slower though the initial value remains almost unchanged and this effect becomes more pronounced with the elevation of the heating temperature. It is also seen that in such a case as (4) where the increase in the final value is much pronounced, not only the initial value increases but the emission also increases after the initial decay, and that the change becomes less marked due to the repetition of the heating, as seen from (5) and (6). In this case as well as in the case of high-temperature heating of the cathode, the decay characteristic can be restored to the initial state by applying a high anode voltage.

(b) Using a-type tube, changes in decay characteristic were examined by heating a cathode at 900°K for 1 hr placing the tube alternately in air (treatment A) and in melting ice (treatment B). The result is shown in Fig. 8. The observation was always carried out at 810°K and 80 V. It is seen from the figure that the initial value decreases in both cases, and that the final value remains almost unchanged in the case of treatment B where a getter deposit does not get warm, while in the case of treatment A the final value increases.

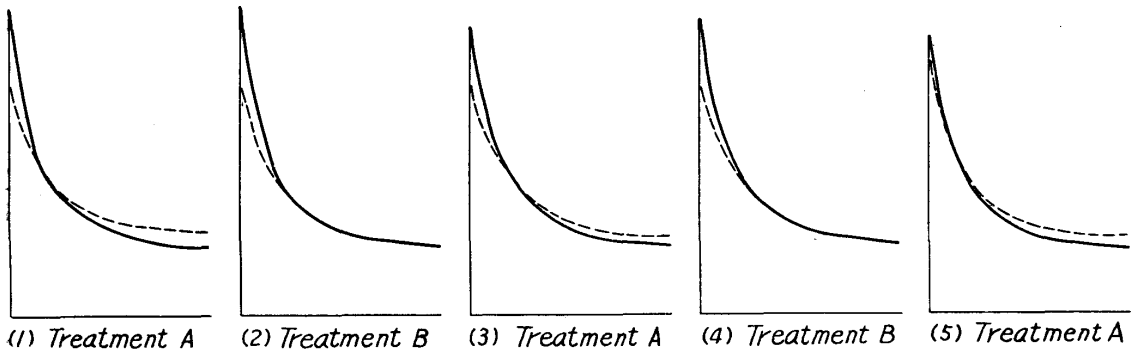

Fig. 8. Change of decay characteristic by high-temperature heating of cathode in the case where tube was placed in air (A), and also the case where tube was immersed in melting ice (B) (a-type tube). Solid and dotted curves represent characteristics before and after heating respectively. Observation at $T = 810°K$ and $E_p = 80$ V.

(c) Using an experimental tube of b-type which has a separate getter chamber so that a getter deposit will not get warm by high-temperature heating of the cathode, the decay characteristic was examined by high-temperature heating of cathode with heating the getter deposit from outside of the tube kept in air (treatment B), and with the tube kept in air only (treatment A). In both treatments the cathode was heated at 970°K for 30 min and observation was always made at 870°K and 80 V. Fig. 9 shows the results. Temperatures for heating the getter deposit were 100°C and 150°C in the cases (2) and (4) respectively. It is found that in the case of treatment B such as (2) and (4), the initial and final values increase and the decay becomes slower, while in the case of treatment A such as (1), (3), and (5), the characteristic remains almost unchanged. Specially in the case of (4), the emission increases after the decay.

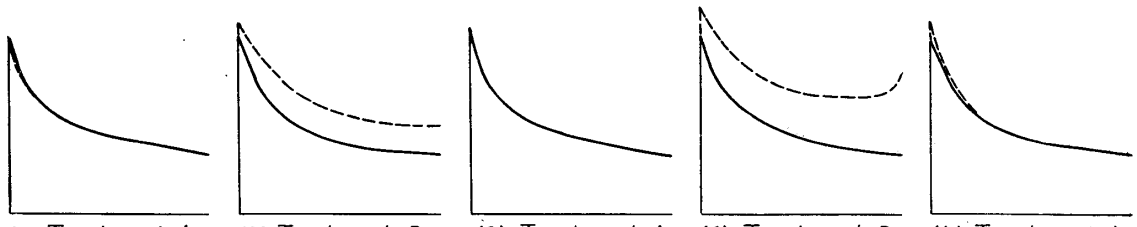

Fig. 9. Change of decay characteristic by the treatment of heating cathode only (A) and of heating cathode and getter deposit (B) (b-type tube). Solid and dotted curves represent characteristics before and after treatment respectively. Observation at $T = 870$°K and $E_p = 80$ V.

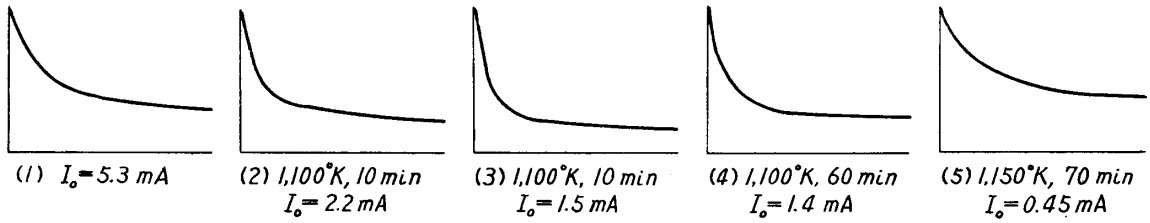

Fig. 10 Change of decay characteristic by heating cathode at very high temperature while cooling a getter deposit (a-type tube). Observation at $T = 855$°K and $E_p = 80$ V.

(d) Fig. 10 shows the result with a-type tube obtained in the case where the cathode was heated at very high temperature, cooling the getter deposit by immersing the tube in melting ice. The observation temperature was 855°K and the anode voltage 80 V. Initially, the decay characteristic was such as shown in (1) and the initial value I_0 was 5.3 mA. If the cathode is heated at 1,100°K, as shown in (2) and (3), the decay becomes more rapid with the prolongation of the heating period and the initial value decreases to 2.2 mA and 1.5 mA, respectively, showing the deactivation of the cathode. By further heating the cathode at 1,100°K and 1,150°K, however, the decay becomes slower, on the contrary, as seen from (4) and (5), though the initial value still decreases to 1.4 mA and 0.45 mA, respectively.

(iii) Extraordinary decay characteristic

In some tubes, an extraordinary decay characteristic was often observed in which the emission increased beyond the initial value with time and then decreased through the maximum. In this characteristic both the increase and the decrease of emission are more pronounced with higher anode voltage. If the emission current is drawn out at the observation temperature by continuously applying high anode voltage, the emission in the characteristic ceases to increase and only the slow decay is observed. However, the characteristic is restored again to the extraordinary one if the anode voltage is switched off and the cathode is kept at the observation temperature for a while. Such an extraordinary characteristic always appears after heating the cathode at high temperature or heating the getter deposit in a tube which initially shows a slow decay. Fig. 11 shows an example which represents the change in the decay characteristic in a-type tube which shows

a slow decay, when the cathode was heated at high temperature. In the case of treatment A, the cathode was heated at 950°K for 30 min with the tube located in air, while in the case of treatment B a tube was immersed in melting ice under

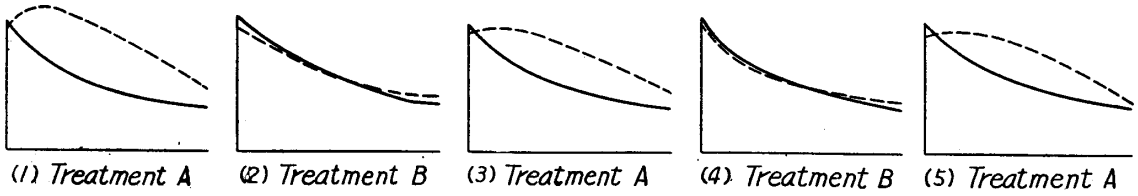

Fig. 11. Appearance of extraordinary decay characteristic by high-temperature heat treatment of cathode (a-type tube). In the cases of (1), (3), and (5) tube was placed in air and also in the cases of (2) and (4) tube was immersed in melting ice. Solid and dotted curves represent characteristics before and after treatment respectively. Observation at $T=830$°K and $E_p = 80$ V.

the same condition as heating the cathode in the former case. The observation temperature was 830°K and anode voltage 80 V. It is seen from the figure that in the case of treatment A such as (1), (3), and (5), a mountain-shaped extraordinary characteristic appears, while in the case of treatment B such as (2) and (4), change in the characteristic is slight, and from the comparison between (1), (3), and (5), that the extraordinary phenomenon becomes less by repeating the heat treatment of the cathode.

Also in b-type tube which shows a slow decay, the extraordinary phenomenon appeared when the getter deposit was heated for 30 min at each temperature indicated, as shown in Fig. 12. The observation temperature was 805°K and anode voltage 80 V. It is seen from the comparison between (1), (2), (3), and (4) that

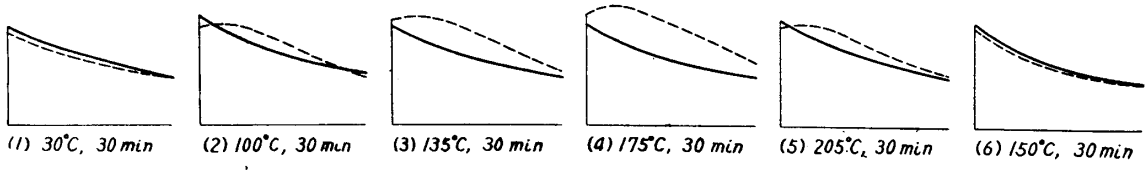

Fig. 12. Appearance of extraordinary decay characteristic by heating a getter deposit (b-type tube). Solid and dotted curves represent characteristics before and after heating respectively. Observation at $T = 805$°K and $E_p = 80$ V.

a remarkable mountain-shaped characteristic appears with the elevation of the heating temperature of the getter deposit, and from (5) and (6) that the change becomes less pronounced by the repetition of the heating. The extraordinary characteristic in the experiments of Figs. 11 and 12 was restored to the initial one by applying a high voltage to the anode, similar to the case of the ordinary decay.

Fig. 13 shows the change in the decay characteristic caused by heating the cathode at very high temperature in b-type tube which initially showed an extraordinary characteristic such as (1) in the figure. The observation temperature was 805°K and anode voltage 80 V. By heating the cathode at 1,100°K for 10 min,

the extraordinary decay characteristic such as (1) becomes a slow decay such as shown in (2) and the cathode is deactivated. On the contrary, from this state, the cathode is activated and the decay becomes very slow such as shown in (3) and then is restored again to the extraordinary one such as shown in (4), by heating the getter deposit at 100°C for 30 min and at 145°C for 1 hr.

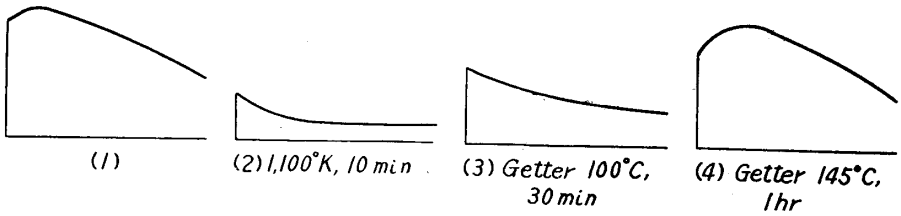

Fig. 13. Change of extraordinary decay characteristic by heating cathode at very high temperature, and its recovery by heating a getter deposit (b-type tube). Observation at $T = 805$°K and $E_p = 80$ V.

3. Low-voltage decay

Some properties of low-voltage decay have been described already in section III. 1. That is, the decay becomes more marked when the anode voltage is lower, it is generally more rapid compared with the case of the saturation current, and the decay at a constant cathode temperature and a constant anode voltage becomes less pronounced with the activation of the cathode. In this section, there will be given several properties of a low-voltage decay other than those mentioned above.

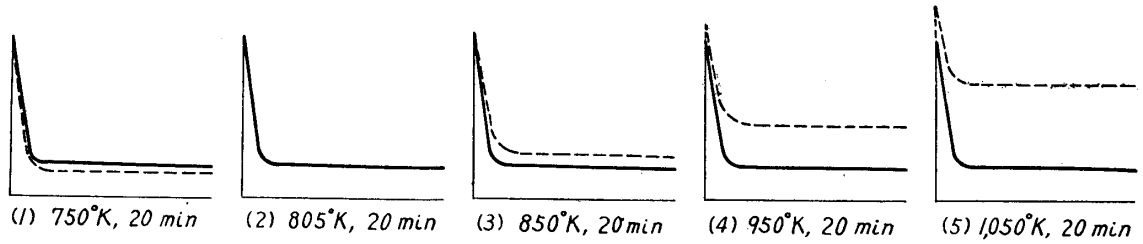

Fig. 14. Change of low-voltage decay by high-temperature heating of cathode (b-type tube). Solid and dotted curves represent characteristics before and after heating respectively. Observation at $T = 805$°K and $E_p = 10$ V.

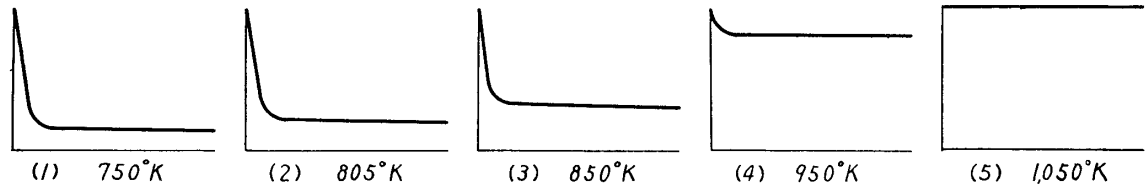

Fig. 15. Temperature effect on low-voltage decay using the same tube as in Fig. 14. Initial values are arranged as of uniform height. Observation at $E_p = 10$ V.

Fig. 14 shows the change in the low-voltage decay characteristic in b-type tube caused by heating the cathode at various temperatures. The observation temperature was 805°K and the anode voltage 10 V. The period of heating the cathode

was always 20 min. As seen from the figure, in the case where the heating temperature is lower than the observation one as in (1), both the initial and final values decrease and the decay becomes more pronounced, while in the case where the heating temperature is higher than the observation one as in (3), (4), and (5), both the initial and final values increase and the decay becomes less pronounced, and this change becomes more remarkable when the heating temperature is higher. The decay characteristic is easily restored to the initial state by keeping the cathode at the observation temperature for a period from a few to over ten minutes.

Fig. 15 shows the low-voltage decay characteristic of the same tube as shown in Fig. 14, observed at the temperatures indicated and at anode voltage of 10 V after keeping the cathode at the observation temperature for 10 min. It is seen from the comparison between Figs. 14 and 15, that the characteristic after the heating (dotted curves in Fig. 14) approaches to the characteristic observed at each heating temperature (curves in Fig. 15), compared with the characteristic before the heating (solid curves in Fig. 14).

It was also observed that the final value in the low-voltage decay characteristic increased without any change in the initial value, when the anode voltage was continuously applied and the current was continuously drawn out, but it was restored to the original one by leaving the tube in air for a while after switching off the anode voltage.

IV. Consideration of experimental results

1. Decay of saturated emission current

(i) Ordinary decay

From the experimental results mentioned in section III. 2 (ii), the following things can be seen: In both cases where a-type (Figs. 7 and 8) and b-type (Fig. 9) tubes are used, and regardless of whether treatment is high-temperature heating of cathode or heating from outside of the tube, the final value always increases and a decay becomes slower if the getter deposit is heated sufficiently, while the final value does not increase, when the getter deposit is scarcely heated. In the case of high-temperature heating of the cathode, the fact that the change becomes more remarkable as the treatment temperature increases, that the change becomes less pronounced gradually by repeating the heat treatment, and that the characteristic can be restored to the initial state by applying high anode voltage and drawing out emission current (Figs. 3 and 4), is qualitatively in good agreement with changes in the case of heating the getter deposit (Fig. 7). Consequently, the phenomenon that a final value increases and a decay becomes slower after high-temperature heating of the cathode may be explained as follows: It may be mainly caused by the enhancement in the gettering action of the getter deposit to residual gases as a result of temperature rise of the deposit by heat radiation from the cathode. The fact that the change becomes more marked as the treatment temperature rises may be due to the enhancement in the gettering action with the

elevation of the getter temperature, and the gradual decrease in the change with the repetition of the heat treatment may be due to the gradual reduction in the gettering action. It seems to be due to the recovery of the gettering action to the initial state through the poisoning action of gases evolving from the anode by electron bombardment, that the decay characteristic which has become once slower by high-temperature heating of cathode is restored to the initial state by applying high anode voltage and drawing out emission current. Therefore, it appears that the main cause of the initial decay of saturated emission current over about 0.1 sec may be attributed to the poisoning action of residual gases on the cathode rather than to the migration of free barium towards a base metal or to the cooling effect of the thermionic emission surface.

In general, the final value increases without any change in the initial value when the getter deposit only is heated (Fig. 7). When the cathode is heated at high temperature with the cooling of the getter deposit, the initial value decreases without any change in the final value (Fig. 8 (2), (4)). When the cathode is heated at high temperature with the tube placed in air, the initial value decreases and the final value increases (Figs. 3, 4, and 8 (1), (3), (5)). In the case where the effect of heating the getter deposit is remarkable and the final value increases pronouncedly, there sometimes appear an increase of an initial value and an increase of emission after it has once decayed (Fig. 7 (4) and Fig. 9 (4)). These phenomena may be explained as follows: In the case of heating the getter deposit only, the initial value is almost unchanged because the vacuum in the tube is nearly constant and an activity of the cathode is not changed, while the final value increases because of enhancement in the gettering action of the getter deposit. In the case of high-temperature heating of the cathode with the cooling of the getter deposit, an activity of the cathode lowers, so the initial value decreases because of the evolution of gases from the parts of the tube heated by heat radiation from the cathode, while the final value remains constant because of the unchanged activity of the getter deposit. It appears that in the case of high-temperature heating of the cathode with the tube placed in air, there occurs a mixed phenomenon of the above two phenomena, that is, the decrease in the initial value due to the evolution of gases and increase in the final value due to the elevation of the getter temperature. Also the case where the final value pronouncedly increases is the case where the activity of the getter deposit is enhanced pronouncedly; therefore, the vacuum is improved and the initial value increases because of the improvement in cathode activity. It seems that in the case where both the initial and the final values increase remarkably, the emission increases again after it once has decayed because the current activation occurs rapidly in a cathode.

In the recovery to the initial state from the slower decay characteristic induced by the heat treatment of the cathode or the getter deposit, the emission decreases slightly with a lapse of time when the cathode is kept at the observation temperature. However, if a low voltage is applied to the anode the emission becomes

almost unchanged. With increasing anode voltage, the emission increases and then decreases through a maximum value. In this case, with increasing anode voltage, the peak in the recovery curves becomes higher and sharper and appears earlier. At anode voltages higher than a certain value, however, the peak intensity decreases (Fig. 6). This phenomenon may be due, perhaps, to the following mechanism: As a result of high-temperature heating of the cathode, keeping a tube in air, the activity of the cathode lowers, due to the evolution of gases from heated parts, as mentioned above. Such a decrease in the cathode activity still continues even when the cathode is kept at the observation temperature after high-temperature treatment, so that the emission may decrease slightly with a lapse of time. By applying a low anode voltage and by drawing out the emission current, however, the cathode is activated slightly and deactivation due to gases is cancelled by this effect, so that the emission remains almost unchanged. Though gases are evolved from the anode and elsewhere by applying a higher anode voltage, the poisoning action of gases scarcely occurs during a short period of the voltage application, owing to the high activity of the getter deposit and the cathode is activated, resulting in the increase of the emission with time in the early stage of the recovery. After a long period of the voltage application, however, the emission begins to decrease through a maximum, because the activity of the getter deposit lowers gradually and the poisoning action of gases begins to exceed the effect of current activation. With increasing anode voltage, the peak in the recovery curve appears earlier and becomes sharper, for both the current activation of cathode and the lowering of the getter activity go on more rapidly. In this case it may be considered that at relatively lower anode voltages, the current activation progresses pronouncedly with increasing voltage, overcoming a slight poisoning action and so the peak intensity increases, while at voltages higher than a certain value the peak intensity decreases with increasing voltage, for the poisoning action of gases becomes remarkable rapidly.

In the case where a low anode voltage is applied and the emission current is drawn out simultaneously with the high-temperature heating of the cathode, the decrease in the initial value is as nearly equal as in the case of only high-temperature heating of the cathode, but the increase in the final value becomes more marked, as compared with the latter case (Fig. 5). On the contrary, when the applied anode voltage is too high, the decay becomes more rapid than in the latter case. This phenomenon can be explained as follows: Though the cathode is activated slightly as a result of applying a low anode voltage and drawing out the emission current simultaneously with the high-temperature heating of the cathode, this effect may perhaps be cancelled out with the poisoning action of small quantity of gases evolved from the anode due to the electron bombardment, so that the initial value may decrease as nearly equal as in the case of only high-temperature heating of the cathode. In the case of voltage treatment, an increase in the final value may become more remarkable, perhaps because the evolution of gases from the anode during the treatment is more pronounced than in the case of heat

treatment only, and consequently, the evolution of gases from the anode at the time of observation becomes less and the poisoning effect in the cathode is reduced. It may be considered, however, that in the case of applying too high an anode voltage, the increase in the final value becomes less than in the case of only high-temperature heating of the cathode, because the evolution of gases increases and the cathode is poisoned by more abundant gases, as compared with the latter case.

After the cathode is heated at very high temperature with the cooling of the getter deposit, the cathode is deactivated and the decay becomes more rapid. On the contrary, when the cathode is extremely deactivated, however, the decay becomes slower (Fig. 10). This phenomenon may be considered as follows: By heating the cathode at very high temperature, the vacuum in the tube becomes worse owing to the evolution of gases from the heated parts. Accordingly, the activities of a cathode and a getter deposit are both lowered, and the decay becomes more rapid. At considerably lower vacuum, the cathode and the getter deposit are both pronouncedly deactivated, while the decay becomes slower, because the cathode may become insensible to the poisoning action of gases, owing to the appearance of contamination on the cathode surface.

The dependence of the decay characteristic of saturation current on the cathode temperature and the anode voltage (Fig. 2) is as follows: (1) The decay becomes pronounced with increasing anode voltage at a fixed cathode temperature. (2) There exists a region where the decay scarcely occurs, and this region extends to higher anode voltage side as the cathode temperature increases. (3) For each anode voltage there exists a cathode temperature at which the decay is most pronounced, and this temperature transfers to higher temperature side with increasing anode voltage. These properties may be explained as follows: (1) With increasing anode voltage the evolution of gases increases and the decay becomes more rapid because of increase in the energy and in the number of electrons bombarding an anode, in spite of the constant activity of the getter deposit at a fixed cathode temperature. (2) At high cathode temperature, the getter deposit gets warm pronouncedly and the gettering action becomes marked. Therefore, the gases evolved from an anode are removed quickly and the decay scarcely shows itself. With increasing cathode temperature, the getter deposit becomes more active to remove more abundant gases and so the decay scarcely occurs until a higher anode voltage is reached. (3) In the case of a fixed anode voltage and at a low cathode temperatures, the getter deposit scarcely gets warm and its activity is very low, while with elevating cathode temperature the evolution of gases increases with increase in the emission and so the decay becomes remarkable. If the cathode temperature becomes still higher the activity of the getter deposit improves pronouncedly due to its temperature rise, while gases are not evolved so much owing to the appearance of the tendency of saturation in the emission, so that the decay becomes less pronounced, with a result that no decay appears at still a higher cathode temperature. Consequently, in the case of a fixde

anode voltage, the characteristic should show the most pronounced decay at a certain cathode temperature. With increasing anode voltage, the cathode temperature showing saturation in the emission becomes higher. Therefore, the evolution of gases surpasses the gettering action until a high cathode temperature is reached, and so the cathode temperature at which the decay is most pronounced increases.

(ii) Extraordinary decay

The extraordinary decay characteristic, in which the emission first increases beyond the initial value and then decays, was observed as a result of high-temperature heating of the cathode or heating the getter deposit in the tubes showing slow decay (Figs. 11 and 12). However, in the case of high-temperature heating of the cathode with the cooling of the getter deposit in melting ice, little change occurred in the decay characteristic (Fig. 11 (2), (4)). Accordingly, the phenomenon in which the extraordinary decay appears through high-temperature heating of the cathode may be attributed to the enhancement in the activity of the getter deposit due to its temperature rise, similar to the case of an ordinary decay. It should be noted that in these cases the decay before the heat treatment is always slow. This seems to be due to high activity of the getter deposit. In such a state, therefore, by further improvement of the getter activity due to heat treatment, the emission will increase rapidly owing to the current activation, and the emission curve will show a peak, similar to the recovery phenomenon caused by the application of the anode voltage in the case of an ordinary decay. From this consideration, it can be easily explained that the higher the anode voltage, the more marked the increase in emission and the decay become.

The extraordinary characteristic induced by high-temperature heating of the cathode or heating the getter deposit is restored to the initial slow decay by applying a high anode voltage and drawing out the emission current. This may be due to the lowering of the getter activity by gases evolved from the anode, similar to the case of an ordinary decay, and the gradual decrease in the change by the repetition of heating the cathode or the getter deposit (Figs. 11 and 12) may result from the reduction in the gettering action of the getter deposit. In an experimental tube showing the extraordinary decay, by heating the cathode at a very high temperature, it is deactivated and the characteristic begins to show only a slow decay, and then by heating the getter deposit sufficiently the cathode is activated and the characteristic can be restored to the initial state (Fig. 13). These phenomena may be explained by the lowering of the cathode and getter activities due to the lowering of vacuum and by the recovery of them respectively. After a high anode voltage is applied and the emission current is drawn out continuously, the increase in the extraordinary characteristic disappears and only the decay shows itself. However, the characteristic can be restored to the initial state by switching off the anode voltage and keeping the cathode at the observation temperature for a while. These phenomena may also result from the reduction of the getter activity by the lowering of vacuum and by the recovery of it respectively. Accordingly,

the main cause of the extraordinary decay may be attributed to the poisoning action of gases, similar to the ordinary decay.

2. Low-voltage decay

It is very interesting that the initial decay generally more rapid than the decay of saturation current was observed at lower anode voltages. Among several tubes observed, there were some tubes which did not show the low-voltage decay at anode voltages higher than 2 V used in this experiment. However, considering from the fact that the low-voltage decay became less pronounced at fixed cathode temperature and anode voltage with increasing activation, the low-voltage decay might perhaps be observed even in those tubes which did not show this decay at anode voltages higher than 2 V, when the observation was made in the state of lower activity or at a very low anode voltage below 2 V. Consequently, the existence of the low-voltage decay is considered to be a general property of the tubes used in this experiment.

In the case of the decay of saturation current, the contamination of the anode is almost out of question, while in the case of the low-voltage decay it seems to be a main cause. D. A. Wright[7] found that in diodes in which a thin film of BaO had been deposited on anode surface, anode current was decayed below the initial value by applying 2~3 V to the anode, and he explained this as being caused by the potential drop at the outer surface of the film due to the charging up rather than by the lowering of the emission. In the present experiment, the dependence of the low-voltage decay on the state of the anode surface was not examined. However, various properties observed here seem to be explained qualitatively by assuming that the low-voltage decay is caused by charging up of poorly conductive contamination deposited on an anode surface.

The low-voltage decay, in general, occurs more rapidly and the emission current becomes stable earlier than that of the saturation current (Fig. 2). This property may be easily explained by assuming that the charging up of the anode contamination reaches an equilibrium state rapidly after the anode voltage is applied.

The decay becomes less pronounced with increasing anode voltage at a fixed cathode temperature (Fig. 2). This property may be also explained as follows: If an anode voltage is applied and a current is drawn out, the contamination deposited on the anode is bombarded by electrons and the temperature of its surface increases, and if the energy of bombarding electrons exceeds the decomposition energy of the contamination, its surface decomposes and free barium (or strontium) is produced. These effects improve the electrical conductivity of the contamination surface and diminish the charging up. At higher anode voltage these effects may become more remarkable and the decay diminishes because of the increase in the energy and in the number of bombarding electrons.

The decay diminishes with increasing cathode temperature at a fixed anode voltage, except in the region D where the decay of saturation current occurs

(7) D. A. Wright, Brit. J. Appl. Phys., **5** (1954), 108.

simultaneously. Again, the higher the cathode temperature is, the lower the anode voltage is at which the decay disappears (Fig. 2). This fact is independent of the activity of the getter deposit because this can be observed on b-type tube having a separate getter chamber (Fig. 15). Consequently, it seems that with increasing cathode temperature at a fixed anode voltage, the temperature of anode contamination becomes higher and also the effects of electron bombardment to the contamination (the temperature rise and the decomposition effect) becomes remarkable owing to a larger anode current. The conductivity of the contamination surface, therefore, is improved and the decay diminishes. Since the increase in the cathode temperature as well as that in the anode voltage has an effect of diminishing the decay, it disappears at lower anode voltage with increasing cathode temperature.

With the activation of the cathode, the decay becomes less marked at a fixed cathode temperature and at a fixed anode voltage. This phenomenon is explained as follows: It is considered that, in the case of a high cathode activity, the contamination on the anode evaporating from the cathode during the activation treatment contains more abundant free barium (or strontium) and is more conductive than that evaporating from the cathode with lower activity. When the cathode is activated by drawing out the emission current, the contamination on the anode is partly decomposed by electron bombardment and the conductivity of the contamination is also improved. In addition, in the state of high activity, the effects of electron bombardment to the contamination at the time of observing decay characteristic is remarkable and the conductivity is much improved, because the anode current is larger than that in the state of lower activity. Owing to the above superposed effects the charging up of the contaminated surface is reduced and the decay diminishes in the case of high activity.

In b-type tube, the initial and the final values decrease or increase by heating the cathode at temperatures lower or higher than the observation one, and in both cases the decay characteristic approaches that observed at the treatment temperature and at the same anode voltage. The recovery to the initial state from the state after the above treatment can be made by keeping the cathode at the observation temperature for a while (Figs. 14 and 15). This phenomenon seems to be almost independent of the gettering action, because it is observed in b-type tube. This may be explained by assuming that the cathode is deactivated or activated by heating the cathode at temperatures lower or higher than the observation one. It is also reasonable physically for the cathode to be restored to the initial state by keeping the cathode at the observation temperature for a while.

If the observation voltage is continuously applied and the current is continuously drawn out, the final value increases without any change in the initial value. However, this state can be recovered to the initial one by switching off the voltage and by keeping the cathode at the observation temperature for some time. It may be considered that in the case where the observation voltage is continuously applied and the current is drawn out, the final value increases due to the effects of electron bombardment above mentioned, and that by switching off the voltage and

by keeping the cathode at the observation temperature for some time, the decay characteristic in the initial state appears again, because the surface temperature of the contamination is restored to the initial one and a small amount of free metal atoms produced at the contamination surface perhaps diffuses to the inside, making the surface state restored to the initial one.

From the above considerations, the main cause of the low-voltage decay may be attributed to the contamination deposited on the anode surface, as Wright mentioned.

Summary

In order to clarify the cause of the initial decay of thermionic emission from oxide-coated cathodes, the initial decay phenomenon over about 0.1 sec was studied on diodes of two kinds — experimental tubes having an ordinary construction and those having a getter chamber separated from the tube for measurements — having a (BaSr)O coated cathode.

In the tubes having ordinary construction, when the cathode is heated at high temperature, the initial decay of the saturation current at the observation temperature becomes slower than that before heating. However, the decay characteristic is recovered to the initial state by applying a high anode voltage and drawing out the emission current. These phenomena are so similar to the changes in the case of heating the getter deposit in the tubes of ordinary type or tubes having a separate getter chamber that they seem to be caused mainly by an improvement in the getter activity due to its temperature rise by heat radiation from the cathode and the recovery to the initial state of the getter activity due to the evolution of gases from the anode bombarded by electrons. Accordingly, the main cause of the initial decay of the saturated emission current over about 0.1 sec may be attributed to the poisoning action of residual gases in a tube.

In observing the dependence of the initial decay characteristic on the cathode temperature and the anode voltage, besides the decay of saturation current hitherto well-known, more rapid initial decay was observed at a lower anode voltage than the former. The properties of this decay were found to differ pronouncedly from those of the decay of the saturation current; for example, the decay diminishes with increasing anode voltage at a fixed cathode temperature. Various properties observed on this decay were explained qualitatively, assuming that the cause of it may be attributed to the drop of the anode potential due to the charging up of contamination on the anode surface.

In conclusion, the author wishes to express his sincere appreciation to Professor Tadatosi Hibi, under whose guidance this investigation was performed, for his helpful advice and constant encouragement.