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INITIAL HEATING STAGE OF EXPLODING WIRES

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Electron emission from exploding wires is studied by measuring the anode current produced in a vacuum diode by heating a tungsten emitter by high density current pulses. Under conditions when the potential drop in the diode is smaller than the ionization potential of the tungsten vapor, an anomalously large value of the anode current is observed. These anomalies, which are absent during stationary incandescence, appear regularly at a definite stage of heating of the metal with high-density current. The physical nature of the phenomenon is not yet fully understood.

INTRODUCTION

THE investigation and practical utilization of wires exploded by electric current has been recently a subject of much attention.[1)] Nonetheless, the explosion process has not yet been adequately explained.

We consider below phenomena occurring in a vacuum diode whose emitter is the investigated wire. These phenomena are observed in the initial stage of heating of the wire, and are of interest in themselves; nor can we exclude beforehand the existence of a possible connection with the explosion which occurs after the melting of the metal.

When a tungsten emitter is heated almost to melting by a current pulse with $j \gtrsim 10^6$ A/cm^2, a current pulse I, appears in the anode circuit of the diode, many times larger than the Langmuir value I* permitted by the space charge.[4] The excess of I over I* would be natural, if it were due to a burst of charge or to neutralization of the space charge by the ions. However, in [4] we have reached the conclusion that in the case of sufficiently strong pulsed heating of the emitter, under conditions which are favorable for the occurrence of ions, the current I becomes anomalously large because of a change in the state of the emitter itself. The maximum value of I, observed under these conditions with non-destroyed wires[5] was in the case of tungsten approximately 100 times larger than a normal emission at the melting temperature T_m (I_m = 480 A/cm^2).[6,7] In experiments with nickel,[8] for which $I_m = 3 \times 10^{-6}$ A/cm^2, a value $I \approx 50\ I_m$ was obtained ($50\ I_m < I^*$ under the conditions of the experiments with the nickel).

On the other hand, it is known that Langmuir's law is not violated at the maximum possible stationary heating of filament cathodes and, all the more, no excess of the anode current I over I_m is observed. Thus, if the unusually large value of I

1)See the report of the Conference on Exploding Wires held in 1964[1]. Papers delivered at the two earlier conferences were published in the form of separate collections[2,3].

in experiments with large currents is actually determined by the state of the emitter, then this state should be unusual. The anomalies in the state of the wire can be due either to inhomogeneities produced in it by the strong current, or by the state of the metal itself. In the experiments under consideration, no inhomogeneities of the heating of the wire prior to its melting were observed.[2)] Thus, the excess of I over I_m offers evidence of an anomalous state of the metal, in which its electron emission is unusually large. Such an interpretation of the experimental data is apparently in poor agreement with the theory of metals[3)] and, furthermore, calls for an explanation of the causes of the violation[4)] of the Langmuir law, that is, the excess of I over I*.

In this paper we returned to this question, but we were unable to find an explanation for the observed excess of I over I_m and I*. On the other hand, the possibility of anomalous emission has not been theoretically demonstrated, nor was it proved by any other experiments. Therefore the question of the causes of the unusually large emission of the anode current still remains open.

GLOW OF WIRES

We shall henceforth use the results of an unpublished paper by L. N. Borodovskaya. In this work, carried out in 1955 with the author of the present article participating, there was investigated by a photoelectric method the glow of wires with a current $j \sim 10^6$–10^7 A/cm². An area study[8] of the oscillograms of the voltage on the wire $V_R(t)$ has disclosed the following.

1. The photocurrent oscillograms $I_{ph}(t)$, characterizing the radiation from the wire in the visible part of the spectrum, have kinks corresponding to the start of melting (m), the end of melting (m′), and the explosion of the metal (c) (Fig. 1).

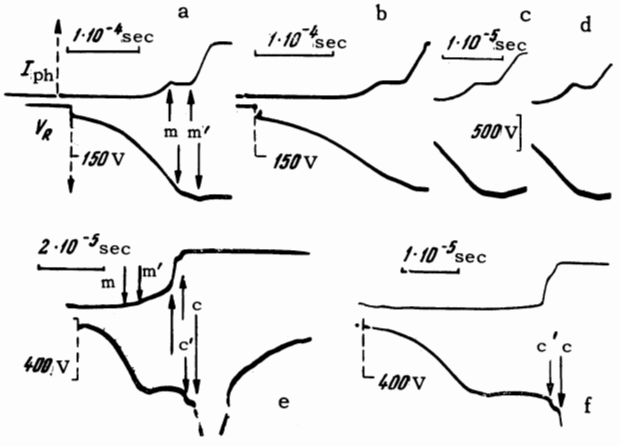

FIG. 1. Oscillograms of the photocurrent $I_{ph}(t)$ (upper lines of each pair) and of the voltage $V_R(t) = iR(t)$ (lower lines), obtained by L. N. Borodovskaya. The points m and m′ correspond to the start and end of melting and c to the explosion of the metal. R is the wire resistance, d the diameter, l its length, and i the current (which remains almost constant after it is switched on). The lower lines are shifted relative to the upper ones to the right. The growth of the ordinates for I_{ph} is limited by the recording system. a – tungsten in air, d = 0.077 mm, $l \approx 30$ mm, current density $j = 4i/\pi d^2 = 1.6 \times 10^6$ A/cm²; b – molybdenum in air, d = 0.1 mm, $l = 38.3$ mm, $j = 1.4 \times 10^6$ A/cm²; c and d – tungsten in air, d = 0.077 mm, $l = 2.7$ mm, $j = 3.7 \times 10^6$ A/cm² (c – surface finish different than in the experiment a, d – after incandescence in vacuum); e – tungsten in glycerin, d = 0.1 mm, $l = 10.8$ mm, $j = 3.7 \times 10^6$ A/cm²; f – tungsten in glycerin, d = 0.077 mm, $l = 9.8$ mm, $j = 4.2 \times 10^6$ A/cm². In experiment e, and especially in f, the sensitivity of recording of I_{ph} has been reduced.

2. The value of the photocurrent at the instant of the start of melting $I_{ph}(t_m)$ turns out to be the same, within the limits of measurement accuracy (20%), for slow ($t_m \sim 3$ sec) heating of the metal (in vacuum) and for heating with high-density current.

3. The change of I_{ph} on melting,[5)] that is, the ratio $I_{ph}(t_{m'})/I_{ph}(t_m)$ does not depend on the value of the current j and agrees with the data obtained for molybdenum under stationary conditions ([12], p. 366).

4. The section of the I_{ph} oscillogram following

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2)The value of the wire resistance at the instant of melting, measured from the oscillograms, agrees well with the calculated data for uniform heating[8,9].

3)According to the data[10] for tungsten, the anomalous emission can appear for $j \gtrsim 10^7$ A/cm² as a result of "superheating of the electrons." In fact a large current I appears already when $j \approx 10^6$ A/cm² and lasts quite long (more than 10^{-5} sec) after turning off the pulse j. See also the data presented below on the glow of the metal.

4)According to Langmuir's complete formula[11] the anode current depends on the magnitude of the emission I_0 and the emitter temperature T. The values of I_0 and T for the anomalous state of the emitter are unknown, so that the applicability of the formulas of [11] for this state has not been verified. By I* is meant here the Langmuir value of the anode current at maximum possible stationary heating of the tungsten emitter.

5)It has been noted for tungsten that, regardless of the value of j, the current I_{ph} drops slightly after the start of the melting (m). The magnitude of this drop depends on the prior heating of the wire (apparently, on the recrystallization) and on its surface finish (Figs. 1, a, d).

To avoid a discharge flash during the measurement of $I_{ph}(t_{m'})/I_{ph}(t_m)$ the wire was placed in air, nitrogen, water or glycerin.

the melting of the metal (m′) and prior to its explosion (c) depends on the current density j: on going over to larger j the value of $I_{ph}(t_c)$ increases because in the case of larger j the explosion occurs at larger values of the energy.[8]

Thus, prior to melting (meaning also under conditions in which "anomalous emission" is observed[5,8]) no singularities that might be connected with the large current density j were observed in the glow of the metal. This means, apparently, that when $t < t_m$ the metal as a whole does not become superheated, or that the electrons do not become superheated.[10]

Control photographs of tungsten wires, taken with exposure $\sim 3 \times 10^{-6}$ sec show that the wire glows uniformly at currents $j \gtrsim 5 \times 10^6$ A/cm^2. Irregularities are manifest only at the instant of explosion and show the appearance of jumps (c′) on the oscillograms of I_{ph} (Figs. 1, e, f). When j decreases below $\sim 2 \times 10^6$ A/cm^2 the inhomogeneities of the glow of the melting wires (diameter ~ 0.1 mm) become considerable. However, until the instant of melting t_m the glow remains uniform for all values j at which the heat transferred to the ends can be disregarded.

PROCEDURE AND AUXILIARY EXPERIMENTS

The investigated tungsten wires (diameter $d_e = 0.077$ mm, length $l_e = 0.15$–5 mm) served as emitters in a vacuum diode and were located along the axis of a nickel cylinder (diameter $d_c = 10$ mm, length $l_c = 40$ mm) which served as a collector of electrons. The wires were heated by single rectangular pulses of current ~ 30 A (current density $j \approx 6.5 \times 10^5$ A/cm^2). At the instant when the pulse was turned on, the pressure in the diode was $\sim 3 \times 10^{-6}$ mm mercury, and the electrodes were first heated in vacuum for 30–40 min.

Simultaneously with the current I flowing in the collector circuit, we registered the glow of the wire with the aid of a photomultiplier and an antimony-cesium cathode. The oscillograms of the photocurrent I_{ph}, the singularities of which were considered above, made it possible to trace the variation of the state of the emitting surface. The currents I_{ph} and I were recorded with a two-beam oscilloscope using the circuit shown in Fig. 2.

The Langmuir current I* was determined in many cases directly from the oscillograms. In addition, I* was estimated from the measurements made in the stationary mode with the same collector, but with a new emitter in the form of a long tungsten wire ($l_e = 44$ mm, $d_e = 0.077$ mm). At the maximum possible heating current in this wire,

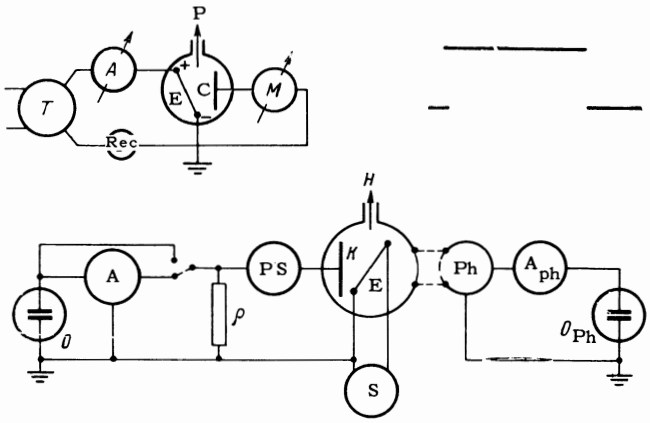

FIG. 2. Diagram of principal setup (below) and diagram of insulation for estimating the current I* at V = 0 (above). E – emitter (wire), C – collector, P – pump, S – pulse source (form of the pulse can be seen from the oscillogram on the upper right), PS – power supply, A and A_{ph} – amplifiers, O and O_{ph} – two-beam oscilloscope, $\rho = 33$ ohm – input resistance of the amplifier, Ph – photomultiplier (FÉU-29) with power supply, T – transformer, Rec – rectifier, A – ammeter, M – milliammeter.

and at anode voltages V = 200 V and V = 0, the current I* per centimeter of length of the incandescent part of the wire (~ 40 mm) turned out to be 3.9×10^{-2} and $\sim 2 \times 10^{-4}$ A, respectively.[6] For the case V = 0, Fig. 3 shows the dependence of the measured values of I* on a certain emitter temperature T_{av} averaged over the period.[7] What was actually measured was the heating current i_h, for which T_{av} was determined from Langmuir's tables.[6,7] These tables give the exact values of the temperature only for direct current. For intermittent heating current, the limits of the oscillations of the wire temperature were estimated from its cooling after a time $\Delta t = 10^{-2}$ sec, during which the current i_h was turned off,

$$\Delta T < i_m^2 R_m^{(1)} \Delta t / C_m^{(1)} = 460^\circ, \qquad (1)$$

[6] According to the "3/2 law" for a cylindrical anode at V = 200 V the value of I* is found to be practically twice as large as that measured for a half-cylinder.

[7] The result $I^* \approx 2 \times 10^{-4}$ A for V = 0 was obtained when the emitter was heated with alternating current i_h (50 cps) through a rectifier (Fig. 2). During one half-cycle the current i_h is shut off and the wire is equipotential; during the next half-cycle it is positive and receives a positive potential relative to the collector, thus decreasing the current I_M^* measured with the milliammeter M. We therefore have $I_M^* < I^* < 2I_M^*$. In order not to overestimate subsequently the ratio I/I*, it was assumed that $I^* \approx 2I_M^* = 2 \times 10^{-4}$ A. An exact determination of I* for long wires is unnecessary, since according to these data it is possible (by decreasing I* in proportion to the rate l_e) to obtain an approximate value I* for the case of short wires welded to a thick holder.

where $R_m^{(1)} = 2.5\,\Omega$ and $C_m^{(1)} = 2 \times 10^{-4}$ J/deg is the resistance and the specific heat per centimeter of wire ($d_e = 0.077$ mm) at a melting temperature $T_m = 3655°$ K, $i_m = 1.92$ A—the direct current compensating the cooling of the long wire at $T = T_m$. All these quantities were obtained from the tables of [6, 7]. As seen from Fig. 3, a change of T_{av} by $\sim 500°$ changes the current I* by not more than two times. Therefore, according to Fig. 3, the value $I^* \approx 2I_M^* = 2 \times 10^{-4}$ A is convenient for a rough estimate of the Langmuir current near the melting point.

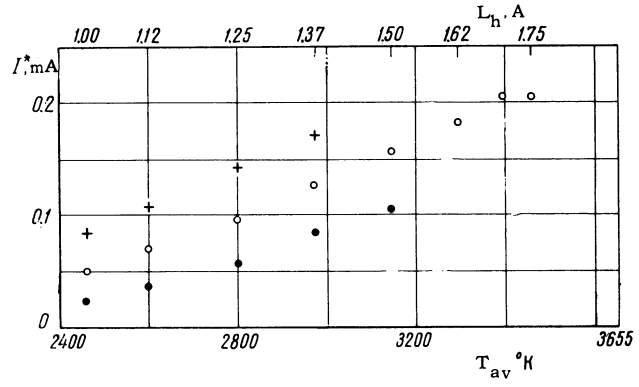

FIG. 3. Current I* ($I^* = 2I_M^*$) per centimeter of length of tungsten wire with $d_e = 0.077$ mm, $l_e = 44$ mm. o – V = 0, + – V = 1 V, • – V = –1 V. The currents I_M and i_h were measured with instruments M and A (Fig. 2). When $i_h = 1.75$ A, the wire disintegrates. (The potential drop on the instrument M which does not exceed 0.1 V is disregarded.)

REPETITION OF THE EXPERIMENT WITH ANODE VOLTAGE 400–800 V

The results of these experiments coincided with the earlier ones.[4] One of the obtained series of oscillograms is shown in Fig. 4. In the first pulse,[8] to which Fig. 4, b pertains, the wire was still inadequately outgassed, and a discharge flashed in the diode. The current to the collector increased sharply in this case and the line of the oscillogram I(t) is broken.

During the time of the next pulse (Fig. 4, c) the discharge no longer occurs but the current I exceeds the Langmuir value I*. This apparently is due to the appearance of ions. After several discharges, when the wire is sufficiently purified, a step marked by the arrow on Fig. 4, d, is regularly observed in the I(t) curve. It was explained earlier[4] that this step corresponds to the Langmuir value of the current I*. For longer pulses

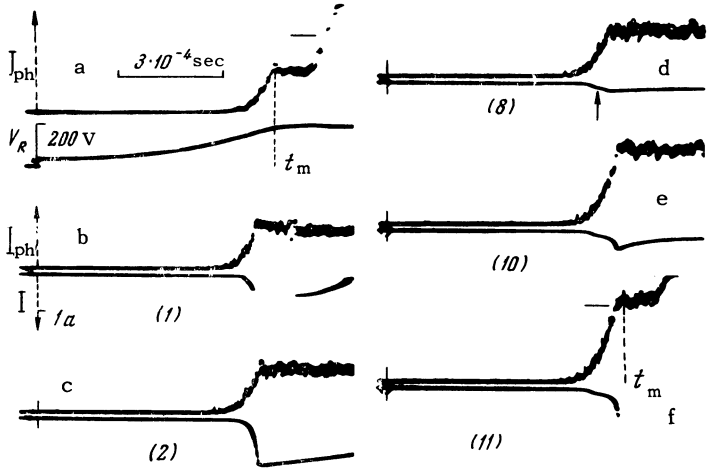

FIG. 4. Upper curves – photocurrent characterizing the glow of a tungsten ($d_e = 0.077$ mm) to arbitrary scale which is the same for figures b-f. Current i = 29 A ($j = 6.2 \times 10^5$ A/cm^2). a – $l_e = 25$ mm, lower curve $V_R(t) = iR(t)$; b–f–series of experiments with the same wire $l_e = 4.7$ mm at V = 540 V. Lower curves – current in collector I which (unlike in Figs. 5, 6, 8) was recorded without an amplifier at $\rho = 47$ ohm. The scales of the time and the current I are shown in Figs. a and b; the horizontal bars in Figs. a and f – limits of linear registration of the current I_{ph}.

(Figs. 4, d, e) we observe the phenomenon in which we are interested, viz, the growth of the current I above the value I*, and the character of this growth for the corresponding instant of time is well reproduced with further repetition of the experiments. Figure 4, f pertains to the last of the experiments in the series, during which the wire is destroyed. From Fig. 4, f we can estimate the value of the temperature T′ at the instant t′ when the excess of I over I* is already well pronounced ($I \sim 2I^*$). To this end we measure on the oscillogram $t_m - t' \approx 3.5 \times 10^{-5}$ sec and, knowing that i = 29 A, we obtain from the condition

$$i^2R(t_m - t') = C(T_m - T')$$

that $T' \approx 3280°$ K (we have used here for the wire resistance R and for its specific heat C the values of $R_m^{(1)}$ and $C_m^{(1)}$ given above).

DECREASE OF THE ANODE VOLTAGE V

If the anode voltage is high, ionization of the residual gases or the metal vapor by the anode field is possible. At low V, other complications arise—the falling of electrons on the collector is hindered by the magnetic and electric fields H_i and E_i connected with the flow of the current i in the wire. From Figs. 5, a and b we see that when V = 0 and V = 40 V, no current flows to the collector until the instant t_{off} when the pulse is turned

[8] The number in the brackets in the oscillograms indicates the serial number of the pulse passed through the given wire.

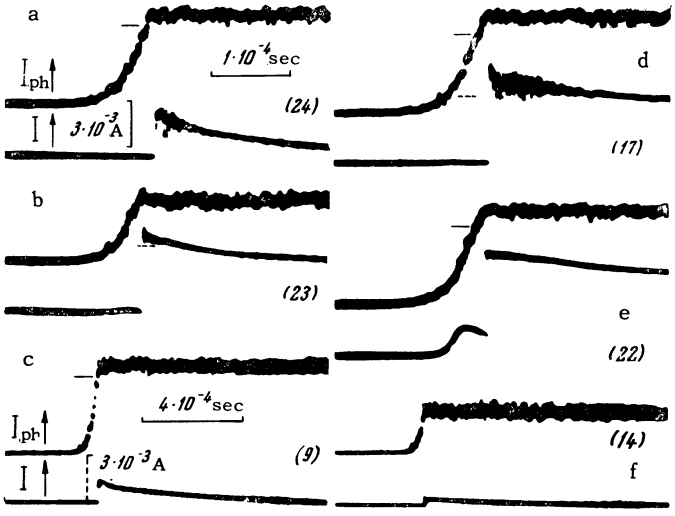

FIG. 5. Photocurrent I_{ph} and current in collector I for a tungsten wire d_e = 0.077 mm at a current i = 32 A ($j = 6.9 \times 10^5$ A/cm²). The start of the oscillograms has been cut off, the current t_{off} when the current I is turned off can be seen from the kink in the I_{ph} and from the jump of the current I. a, b, d, e – experiments with the same wire, l_e = 5.2 mm, at voltages V equal to 0, 60, 40, 100 V, respectively; c, f – experiments with a different wire l_e = 5 mm at V = 0. Scales for a, b, d and e are designated on Fig. a; those for c and f in Fig. c. The solid horizontal bars – limits of linear registration for I_{ph}, dashed–for I.

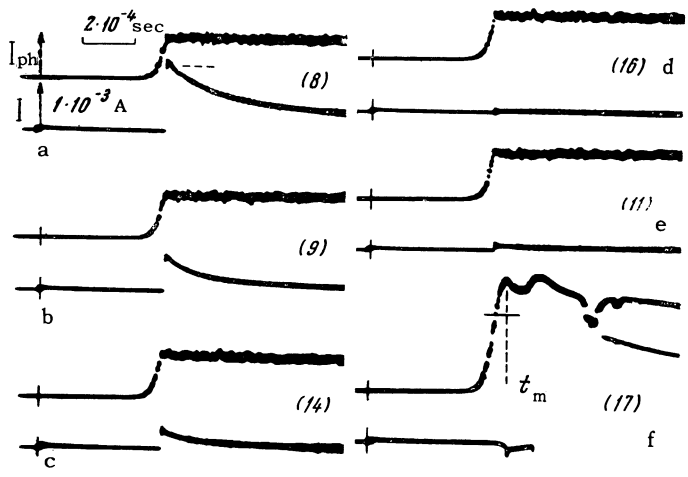

FIG. 6. Series of oscillograms for the current I_{ph} and the current I for a tungsten wire d_e = 0.077 mm, l_e = 5.5 mm at $j = 6.9 \times 10^5$ A/cm². The values of the voltage for a,b,c,d,e and f are respectively 6, 0, –0.4, –2, –2, –2 V. For a,b,c,d, the duration of the pulse is the same; for e it is slightly increased (as can be seen from the increase in I_{ph}) and for f it is strongly increased. The solid and dashed bars are the limits of linear registration for I_{ph} and I.

off, at which instant the fields H_i and E_i vanish and the current I appears abruptly. For $t < t_{off}$ and V = 60 V, the current I is hardly noticeable (Fig. 5, b), and for V = 100 V (Fig. 5, e) it is already appreciable.[9)]

We shall henceforth study the current I after the instant when the pulse i is turned off and there are no fields.

The value of the current after the instant t_{off} depends strongly on the duration of the pulse. For example, when V = 60 V (Fig. 5, b), the current I is smaller than when V = 40 V in the experiment with the longer pulse (Fig. 5, d). For the same anode voltage V = 0, in the case of a longer pulse (Fig. 5, c), the current I is larger than in the case of a shorter pulse (Fig. 5, f). An estimate shows that in all these cases, the maximum value of I exceeds the Langmuir value I*. For example, for Fig. 5, c we have $I_{max} > 1 \times 10^{-3}$ A, whereas according to the data of Fig. 3 we have $I^* \sim 2 \times 10^{-4}$ A/cm × 0.52 cm = 1×10^{-4} A. The dependence of I on V for the case of small V is illustrated by oscillograms obtained with pulses of equal duration (Figs. 6, a, b, c, d). Oscillograms obtained in similar experiments carried out with a different piece of wire were used to plot the de-

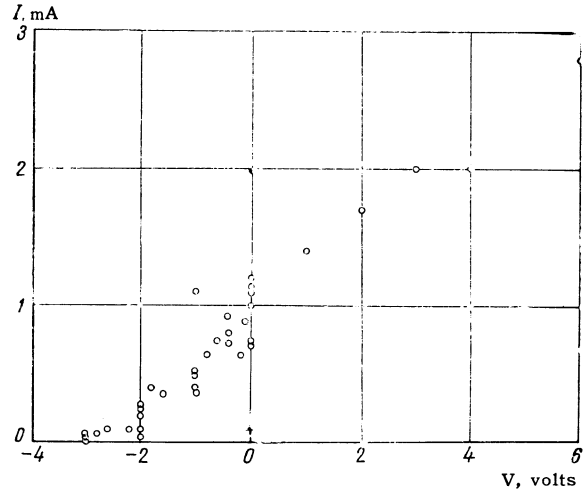

FIG. 7. Dependence of the maximum value of the current in the collector I on the voltage V. All the measurements were made for the same tungsten wire d_e = 0.077 mm, l_e = 5 mm. Pulse duration ≈5.5×10^{-4} sec, $j = 6.9 \times 10^5$ A/cm² (see also Fig. 6). The cross denotes the maximum value of the anode current I* obtained under stationary measurements (Fig. 3) and recalculated for l_e = 5 mm.

9)For the critical value of V, when the current I is blocked by the magnetic field, we have in the case of a cylindrical system of electrodes

$$V_c = 1.88 \cdot 10^{-2} i^2 \left[\log \frac{d_c}{d_e}\right]^2,$$

where i is in amperes and V_c in volts ([13], p. 125). For the experiment in question V_c = 86 V. We take no account here of the field E_i and of the true configuration of the electrodes.

pendence of I on V (Fig. 7). The pulses were not sufficiently uniform here, this being the main cause of the scatter of the points (compare Fig. 6, d with Fig. 6, e). The black circle in Fig. 7 denotes the result obtained at the end of the series of longer pulses, after which the wire also remained intact. Comparing this value with the Langmuir value I* (Fig. 3) recalculated for $l_e = 5$ mm, we get $I \approx 20\, I^*$. We emphasize that in these cases the probability of appearance of ions due to the anode voltage V is very low, since V is smaller than the ionization potential of tungsten $v_W = 8$ V (for nickel, nitrogen and oxygen we have $v_{Ni} = 7.6$ V, $v_N = 14.5$ V and $v_O = 13.6$ V).

SHORT WIRES

We can attempt to explain the excess of I over I* in the case of small V by attributing it to the action of the ions produced prior to the instant of turning on the current i, as a result of the voltage drop along the wire $V_R = Ri$. It is therefore of interest to investigate short wires, for which $V_R < v_W$. Under the conditions in question, it is necessary to have for this $l_e < v_W/R_m^{(1)} i = 1$ mm.

Shorter wires are of interest also because they ensure a rapid cooling of the metal by heat dissipation from the ends. This makes it possible to trace the decrease of the current I from its maximum value to values smaller than I*. Figure 8 shows the results of experiments with the same wire of length $l_e \approx 0.15$ mm for which the maximum value is $V_R \approx 1.2\,V < v_W$. We can judge the cooling of the wire after the instant t_{off} from the decrease of the photocurrent. In the case of a long wire ($l_e = 5.5$ mm, Figs. 6, a, b, c), no noticeable decrease of I_{ph} occurs.[10]

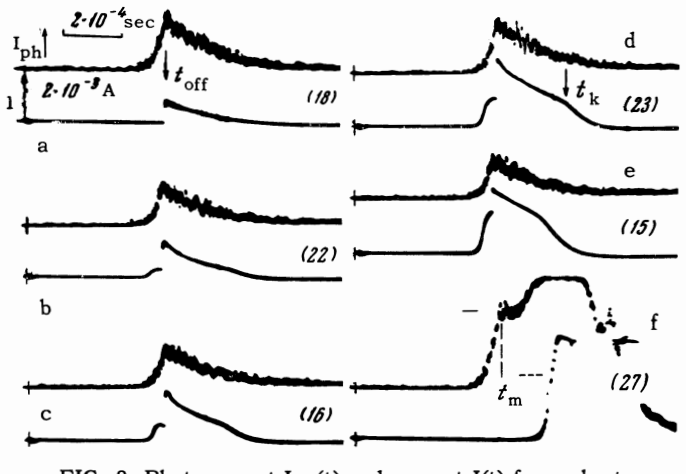

FIG. 8. Photocurrent $I_{ph}(t)$ and current I(t) for a short ($l_e \approx 0.15$ mm) tungsten wire $d_e = 0.077$ mm for $j = 6.9 \times 10^5$ A/cm². For Figs. a, b, c, d, e and f, the anode voltage is respectively 0, 200, 300, 400, 500 and 0 V. In e the pulse duration has been increased and the wire disintegrated. The solid and dashed bars are the limits of linear registration for I_{ph} and I.

Let us consider, first, experiments with large anode voltage V, in which a kink in the I(t) curve is observed at the instant t_k (arrow in Fig. 8, d). Figure 9 shows the dependence of the current I on V, obtained from such kink points. The experimental points for $I(t_k)$ apparently reflect the Langmuir relation $I \sim V^{3/2}$, which is somewhat distorted as a result of the uneven heating of the short wire.[11] The values of $I(t_k)$ obtained from Fig. 8 for V = 200 V are approximately 25% lower than the values of I* obtained by recalculation from data of stationary measurements with a long wire. In this case it is impossible to count on a better agreement, particularly because of the difficulty of determining the lengths of the short ($l_e \approx 0.15$ mm) wire welded to a thick holder.

Thus, in magnitude and in its dependence on V, $I(t_k)$ is close to the Langmuir current.

We see from Fig. 8 that during the course of the time from the instant when the pulse is turned off t_{off} to the instant of the kink t_k the "$^3/_2$ law" of Langmuir is not satisfied, since the I(t) curve decreases and does not go parallel to the abscissa axis at the level $I = I^*$.

The violation of the Langmuir law is demonstrated particularly clearly by comparing Figs. 8a and 8b. In the experiment of 8a, the maximum value of the current I exceeds the Langmuir value I* (the kink point t_k) for the experiment of 8b, although in the first case V = 0 and in the latter, V = 200 V. However, from the results of the measurements in the stationary mode, the Langmuir value I* for V = 200 V is approximately 200 times larger than for V = 0. Consequently, in the experiment of 8a the current I exceeds I* by two orders of magnitude, although the anode voltage is V = 0, and the voltage drop along the wire was raised only to a value $V_R \approx 1.2\,V < v_W = 8$ V.

Thermal ionization is insufficient to cause an excess of I over I* at temperatures 3000–3200° K.[12] This is seen from the fact that the

[10] An estimate by means of formula (1) shows that after a time $\approx 7 \times 10^{-4}$ sec (from the instant t_{off} to the end of the oscillogram in Fig. 6, a) a long wire cools down by $\Delta T < 30°$.

[11] At smaller values of V, when the cooling time $t_k - t_{off}$ is larger, the ends of the wire cool off more. Therefore its effective length for the instant t_k at small values V is smaller than at large values.

[12] The temperature of the wire at the instant t_{off} for experiments 6, a-e and 8, a-e can be estimated from Figs. 6, f and 8, f. Just as for Fig. 4, f, we obtain $T \approx 2950°$K for Fig. 6 and $T \approx 3200°$K for Fig. 8.

Langmuir law is satisfied in tubes with tungsten cathodes, whose stationary heating can be increased at least to 3400° K (Fig. 3). Arguing against thermal ionization as the cause of large value of I is also the character of the decrease of I after turning off the pulse i. For example, in experiments with long wires (Fig. 6, a) the current I decreases by many times, whereas the photocurrent I_{ph} (and consequently also the temperature) remains practically unchanged (according to footnote [10] $\Delta T < 30°$). Thus, the excess of I over I* cannot be attributed to ionization.

On the other hand, a regular dependence of the maximum value of the ratio I/I* on the heating of the wire is observed. This dependence explains, in particular, the larger value of I/I* (by one order of magnitude) in the experiments shown in Fig. 8, as compared with the experiments of Fig. 6. It turns out that the short wires withstand a stronger pulsed heating than the long wires. This circumstance has made it possible to go over in the experiments of Fig. 8 to longer pulses.[13)]

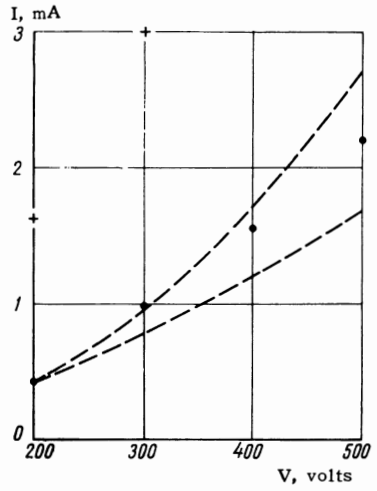

FIG. 9. Dependence of the value of $I(t_k)$ on the anode voltage (black circles). The upper and lower dashed lines are $I = I_{200}(V/200)^2$ and $I = I_{200}(V/200)^{3/2}$ (I_{200} – current for V = 200 V). The crosses denote the maximum values of the anode current $I(t_{off})$ obtained from Figs. 8, b and c. The corresponding values of $I(t_{off})$ for Figs. 8, d and e go beyond the limits of the drawing.

CONCLUSIONS

The excess of the current I over the Langmuir value I* is observed also in those cases when the maximum potential difference in the diode remains all the time several times smaller than the ionization potential of the tungsten vapor. This confirms the lack of justification for attempting to attribute the unusually large value of the current I to ionization.

It has become clear that the excess of I over I* becomes noticeable when the temperature of the metal (W) is still several hundred degrees lower than its melting temperature. The value of I/I* increases with increasing duration of the pulsed I heating the wire, and consequently with increasing heating. This fact can be naturally regarded as the dependence of the anomalous current I on the state of the metal.

After turning off the pulse i, the anomalous current I decreases to its normal value within a time during which the (long) wire has barely any time to cool. Therefore, if the unusual value of the current I is due to the state of the metal, then the singularities of this state are not determined by its temperature alone.

Thus, the experimental data considered above agree with the hypothesis concerning the anomalous state of the metal, and offer no other possible explanation of the observed singularities of the anode current. It must be borne in mind that emission characterizes directly the state of the surface of the emitter. Accordingly, the assumed anomalies can pertain to the state of the surface of the metal and need not necessarily be connected with its volume properties.

[13)] In addition to measuring the $t_m - t_{off}$ (footnote[12)]), it is possible to estimate the maximum heating of the wire from the value of the ratio $\nu = I_{ph}(t_{off})/I_{ph}(t_m)$. For Fig. 8, ν = 0.5-0.6, whereas for Fig. 6, $\nu < 0.4$. The inequality sign is used because for Fig. 6, f $I_{ph}(t_m)$ is outside the limits of the linear registration.

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66