AN EFFECT OF LIGHT ON THE ELECTRON EMISSION FROM HOT FILAMENTS*

By W. H. Crew

Abstract

Photo-electric currents from hot, oxide-coated platinum filaments.—The increase in the electron emission from hot, oxide-coated platinum filaments when illuminated by the full radiation from a water-cooled quartz mercury arc was measured, for different filament temperatures, as a function of potential between filament and anode. The photo-electron currents were large enough to be readily measurable with a galvanometer. Measurements on one filament showed the photo-electron current increasing with potential to a maximum at about 14 volts. For another filament, twice as thick, the maxima were between 2 and 4 volts. In the case of both filaments increasing the temperature shifted the maximum to lower values of potential. No *photo-electric fatigue* was observed. By the use of various absorbing screens and different sources of light it was found that the photo-currents are, for the most part, due to radiations of wave-lengths shorter than λ3000; but that the *long wave-length limit* is somewhat above that value.

Photo-electron currents from other filaments.—In all, four types of filaments were tried: (a) oxide-coated platinum; (b) plain platinum; (c) oxide-coated tungsten; (d) plain tungsten. Of these, only the oxide-coated filaments gave an appreciable emission due to the light.

The possible source of the photo-electrons is discussed and calculations are made as regards their velocity distribution. Results suggest that the action of the light is to free electrons from a thin film of metal of which the work-function varies with temperature of the filament.

THE photo-electric effect, discovered by Hertz in 1887, was first observed in the case of metals by Hallwachs in the following year. This phenomenon has since been studied with regard to its variation with temperature by Stoletow,[1] Zeleny,[2] Thomson,[3] Millikan,[4] Piersol,[5] and others. In 1921, Merritt[6] extended some experiments previously described by Case,[7] and found that in one instance the heating to incandescence of an oxide-coated filament increased its photo-electric emissivity 1400-fold. Obviously, then, photo-currents obtained from hot oxide-coated filaments are enormous when compared with those obtained at normal temperatures, and may be studied by use of a moderately sensitive galvanometer.

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[1] A. Stoletow, Comptes rendus **108,** 1241 (1889).
[2] J. Zeleny, Phys. Rev. **12,** 321 (1901).
[3] J. J. Thomson, Cond. of Elec. Through Gases, p. 239.
[4] R. A. Millikan, Phil. Mag. **14,** 188 (1907).
[5] R. J. Piersol, Phys. Rev. **8,** 238 (1916).
[6] E. Merritt, Phys. Rev. **17,** 525 (1921).
[7] T. W. Case, Phys. Rev. **17,** 398 (1921).

In view of recent work done by Rouse and Giddings[8] and also by Foote and Mohler,[9] the possibility was entertained that the phenomenon might be a result of a secondary effect of the light. More precisely, Rouse and Giddings found that the radiation λ2536 alone produced positive ions in mercury vapor; and Foote and Mohler showed that positive ions could be made to increase greatly the emission from a filament by neutralizing the limiting space charge thereof. Accordingly, experiments were made to see whether the increase of photo-emission with increase of temperature was due directly to the action of the light on the filament or indirectly to the production of positive ions in the surrounding vapor.

A description of the experimental examination of this point, in which the direct action of the light was found to prevail, and a further study of the photo-emission from hot filaments embrace the chief endeavors of this paper.

Apparatus

A two-electrode vacuum tube, 2.5 cms in diameter, was constructed of Pyrex glass as indicated in Fig. 1. One end of the tube was closed by a quartz window Q, fused on by means of a quartz-Pyrex union. Various

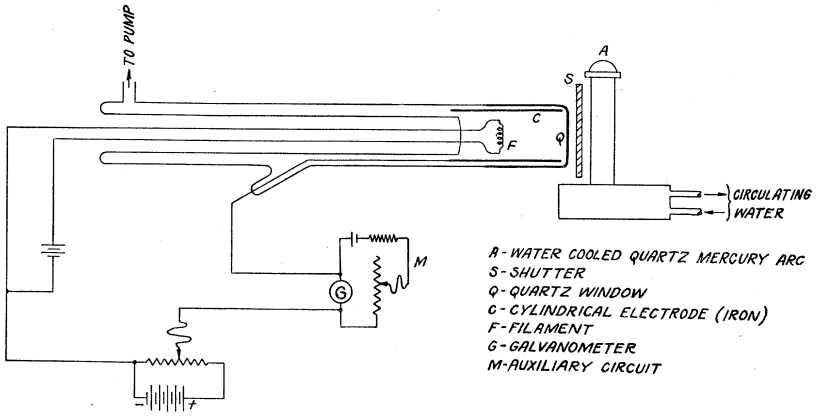

Fig. 1. Diagram of apparatus.

filaments F were used in these experiments and were secured to tungsten leads by means of small clamps made of molybdenum. The plate electrode C was an iron cylinder surrounding the filament. All leads entered the tube through tungsten to glass seals, and no ground glass or wax joints were used.

The evacuating system consisted of a mercury vapor pump backed by a "High-Vac" oil pump, a McLeod gauge, and a liquid-air trap located

[8] C. F. Rouse and G. W. Giddings, Phys. Rev. **25,** 893 (1925).
[9] P. D. Foote and F. L. Mohler, Phys. Rev. **26,** 195 (1925).

next to the tube. For all experiments a pressure of 10^{-6} mm of mercury (per gauge) or better was used.

Various potentials between filament and plate were applied by means of a battery of storage cells and controlled by a potentiometer of the slide wire type. Electronic currents were measured by a Leeds and Northrup high sensitivity low resistance galvanometer, which was capable of measuring the photo-currents from a hot filament, but was practically insensible to the relatively insignificant photo-electric currents from the filament at room temperature. An auxiliary circuit M (Fig. 1) was arranged so that balancing currents could be applied to the galvanometer in order to bring the reading to zero at will. The source of radiation for these experiments was a Cooper-Hewitt quartz mercury arc A cooled by running water. A shutter S was located between the arc and tube to admit the light to the tube as desired.

An electric oven was built to slip over the tube *in situ*. This served not only to bake out the tube but also, in conjunction with the liquid air trap, as a means of removing residual mercury vapor from that part of the apparatus.

Experimental Procedure

In the first set of experiments a strip of platinum foil about 2 mm wide and 10 mm long was used as a filament, and was coated with the oxides of barium and thorium. The tube was then evacuated to a pressure of less than 10^{-6} mm of Hg; and with the pumps running, was thoroughly baked-out for several hours at a temperature of 400°C. After the tube had been allowed to cool, a potential was established such that the electron current was from filament F to plate C, and the galvanometer deflection due to the thermionic current was counter-balanced by the auxiliary circuit M so that the scale reading was zero. The shutter S was then opened, and the total radiation from the mercury arc shone on the filament and caused a deflection of the galvanometer which was noted. A series of readings taken in this manner at different values of applied potential comprised a run, three of which are plotted in Fig. 2. Curve I is a run made before the baking-out process had eliminated the mercury vapor from within the tube. This curve shows a gradual increase of the photo-electron current from zero at 2 volts potential to a saturation value of 4.5 cms deflection at about 6 volts. Curve II is a run made after the mercury vapor had been partly eliminated from the tube, and Curve III is a run made after prolonged baking out had rather thoroughly removed the mercury from the tube. Curves II and III rise almost linearly to a value of photo-electron current at 8 volts potential which is nearly five times as great as that in Curve I.

These curves are taken to show that the removal of mercury vapor from within the tube greatly enhanced the photo-electron emission from the filament, and that therefore this emission was due to the direct action of the light upon the filament and not to a secondary process of ionization of the mercury vapor.

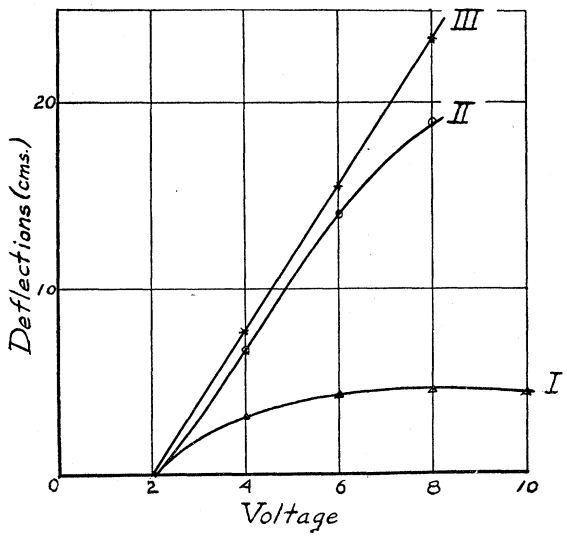

Fig. 2. Photo-electric current from an oxide-coated platinum filament as a function of applied potential.

Operating the tube in the condition in which the mercury vapor had been removed according to the manner previously described, a set of curves, Fig. 3, was obtained giving the photo-current as a function of applied potential for several values of the filament heating current. The curves for which the filament heating current was 2.0 and 2.1 amps. show saturation at about 16 volts; whereas the 2.2 and 2.3 ampere curves rise more abruptly to a maximum value of current and then decrease beyond 14 volts. The 2.4 ampere curve has a maximum ordinate at about 13 volts.

As a check to the consistent performance of the apparatus a run was made at a constant value of 14-volts applied potential at values of filament heating current from 2.0 to 2.4 amps. The galvanometer deflections thus obtained differed from those on the 14-volt ordinate of Fig. 3 by not more than 2 percent. This is taken as an indication of the accuracy with which observations could be repeated.

Upon repeating this experiment with a new oxide-coated platinum filament which was double the thickness of the previous one, the curves of Fig. 4 were obtained. In this case the maxima are seen to be somewhat accentuated and appear in the neighborhood of 3 volts.

There is observed in these curves a shift in the position of the maximum to lower values of applied potential with increase in filament heating current. A similar shift is suggested by the curves of Fig. 3, although the indistinctness of the maxima leaves this fact less certain. However, the shift seems to be perfectly real and consistent.

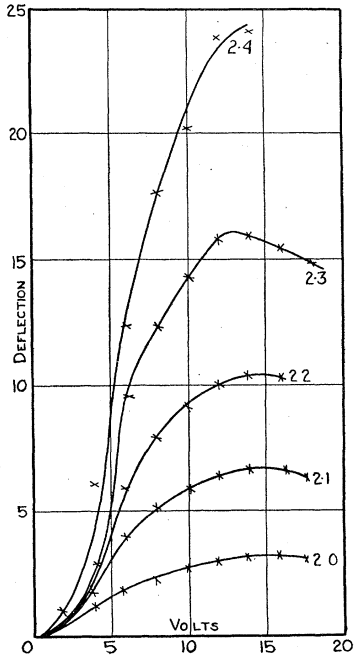

Fig. 3. Photo-electric current from an oxide-coated platinum filament as a function of applied potential for different filament temperatures.

In all of the foregoing curves the points were plotted in order of increasing voltages, and then a few check points were made in the reverse order. The fact that these check points were found to coincide with the curve indicated that the falling off of photo-current at higher potentials was not the result of photo-electric fatigue.

Variation with Wave-length of Incident Light

An attempt was made to observe the photo-emission when the filament was exposed to monochromatic light from a quartz monochromatic illuminator. Because of the reduced intensity of the light and relatively low sensitivity of a galvanometer, no deflections were obtained in this manner. The following experiments indicate, however, that the radiations of shorter wave-lengths are the more effective in producing the photo-emission from the hot filament.

Glass screens of various thickness were interposed between the mercury arc and the quartz window of the tube and the resulting decrease in

galvanometer deflection was noted. A lantern-slide cover glass, 2 mm thick, reduced the deflection due to the transmitted light to zero. Several specimens of thin-blown Pyrex glass admitted of small deflections. These results indicate that the emission of photo-electrons is due primarily to radiations of wave-lengths less than λ3000. A high pressure mercury arc was constructed of Pyrex capillary tubing, and was found to give exceedingly intense radiations down to λ3125. The photo-emission due to this source amounted to about 10 percent of that due to

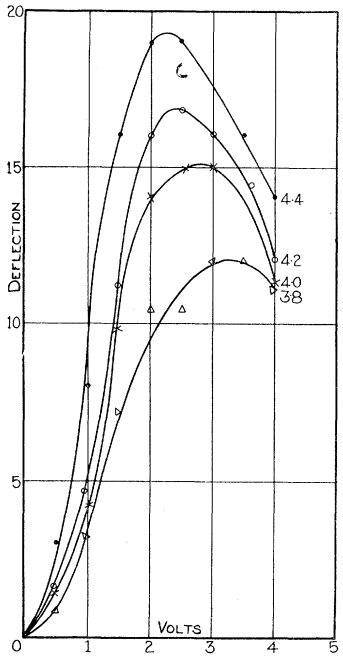

Fig. 4. Photo-electric current from an oxide-coated platinum filament which was double the thickness of that used in obtaining the results shown in Fig. 3.

the quartz arc. These observations indicate that the most effective radiations of the mercury arc are those of shortest wave-length, but that the long wave-length limit (if indeed there is any limit at all) lies above λ3000.

The effect of the removal of mercury vapor from the tube has already been shown (Fig. 2) to increase enormously the emission of photo-electrons. As is well known, mercury vapor in the unexcited condition is capable of absorbing the core of the radiation λ2536. It is probably the reinstating of this portion of the line upon removal of the vapor that is responsible for the increased photo-emission. It has been shown by R. W. Wood that the core of the radiation λ2536 from a mercury arc may be greatly fortified by water-cooling the arc. This was done and

found to increase the emission of photo-electrons about 4-fold. These results indicate that the radiation λ2536 is especially effective in producing the photo-emission.

Observations Made with Other Filaments

Experiments were carried out with the oxide-coated platinum filament replaced by those of (a) plain platinum, (b) plain tungsten, (c) oxide-coated tungsten.

Using a plain platinum filament in the tube and employing the same technique as in the foregoing experiments, no increase of current was observed when the light was admitted to the tube. In fact the thermionic currents from this filament, even when heated to whiteness, were so small as to be barely perceptible on the galvanometer which was used.

The next filament installed was a piece of pure tungsten ribbon 2 mm wide and 0.075 mm thick. When heated this provided ample thermionic currents, but gave no evidence of a photo-emission when light was admitted to the tube. This filament was then given a coating of the oxides of thallium and barium. As a result the thermionic currents were considerably increased and an additional current due to the light from the mercury arc was observed, but this latter was less in proportion to the thermionic current than in the case of the oxide coated platinum. Consequently, it was only by balancing off enormous thermionic currents that the photo-currents became perceptible, and in this condition it was not possible to keep the apparatus steady long enough to make a good run.

This observation with tungsten establishes one important fact; namely, that the photo-electrons are not released from the space-charge; for if they were, it would have been possible to observe photo-electrons with the use of the plain tungsten filament, where there evidently existed an ample space-charge.

Distribution of Electrons

A set of readings was taken with the oxide-coated platinum filament in which the thermionic current was not balanced off. At each value of applied potential, readings were obtained with and without the light shining in the tube, as shown plotted in curves I and II, respectively, of Fig. 5. Curve III is proportional to the difference between curves I and II and represents the current due to the light alone. Here again is observed a maximum value of photo-current at about 2 volts which gradually decreases with higher values of applied potentials. If the logarithm of the ordinates of curve II, Fig. 5, are plotted against the abscissae, one obtains Curve I of Fig. 6. The portion of this curve in the region 0 to 2 volts may be considered as linear and is expressed by the equation

$$\log I_t = CV + k,$$

where I_t is the thermionic current and V is the applied potential. It was recently pointed out by Langmuir[10] that if a current of electrons flowing to a negatively charged collector has a Maxwellian distribution of velocities, the logarithm of this current bears a linear relation to the

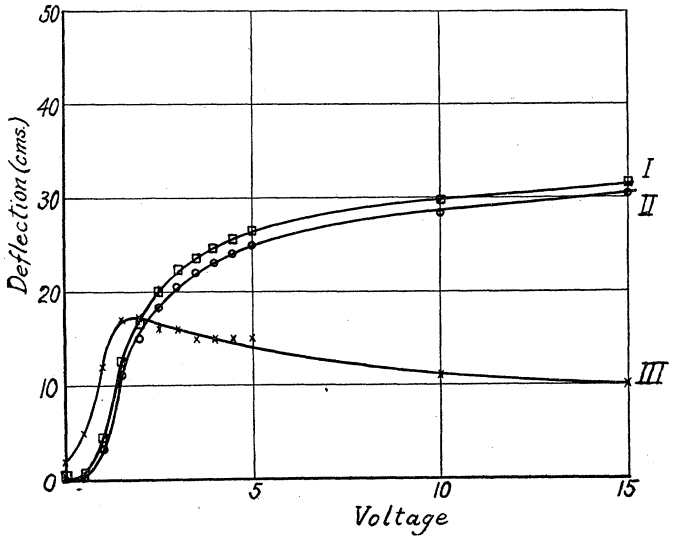

Fig. 5. Curves I and II, total electron emission from an oxide-coated platinum filament with and without light shining in the tube. Curve III is proportional to the difference between I and II.

potential of the collector. This is precisely the condition within the tube below 2 volts applied potential; for at zero volts the cathode is surrounded by a highly negative space-charge. As the plate electrode is made positive up to 2 volts, the negative space-charge is diminished and more electrons flow from filament to grid. This is indicated by the portion of Curve II, Fig. 5, which is concave upwards. Therefore, there is probably a Maxwellian distribution of velocities of the electrons which reach the plate when the thermionic emission is limited by space-charge.

Curve II of Fig. 6 is a semi-logarithmic plot of Curve III of Fig. 5; and here, too, the portion of the curve lying between 0 to 2 volts is linear. From this it may be concluded that the photo-electrons which reach the plate in this region of applied potential have a Maxwellian distribution of velocities.

The slopes of the initial portions of Curves II and I (Fig. 6) are in the ratio 1 to 4. Since the temperature corresponding to the mean velocity of electrons which have a Maxwellian distribution of velocity is inversely proportional to the first power of the slope of the semi-logarithmic plot, the temperature of the photo-electrons in this experiment is of the order 4 times that of the thermo-electrons.

[10] I. Langmuir, Phys. Rev. **26**, 585 (1925).

Discussion of Results

In his Report on Photo-electricity, A. Ll. Hughes[11] gives typical current-voltage curves for the photo-electric emission from pure metals at normal temperatures. In these curves the photo-electric current increases with voltage to a saturation value and there remains constant for higher values of applied potential. The corresponding curves of the present investigation (Figs. 3, 4, 5) are of a distinctly different character, in that the photo-current reaches a maximum and then gradually

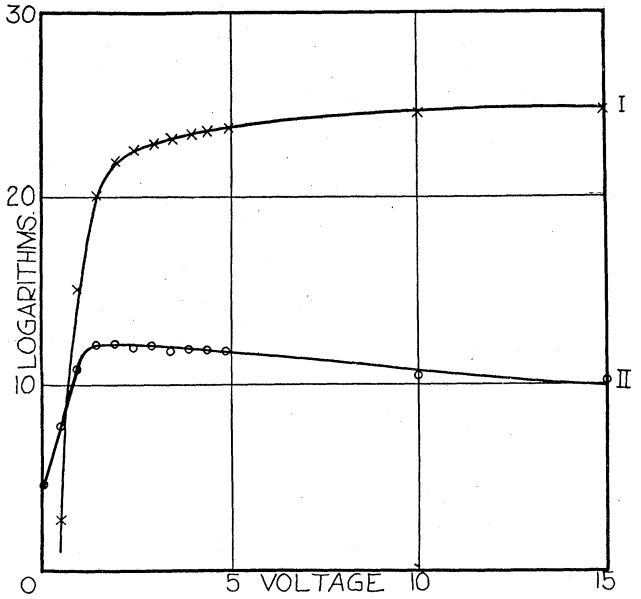

Fig. 6. Semi-logarithmic plot of curves I and II of Fig. 5.

decreases with further increase of applied potential. It remains to be explained, then, how the photo-sensitive surface of a hot oxide-coated filament behaves in order to give rise to a distinct maximum in a current-voltage curve.

A point of view, which has been successfully applied by Ives[12] and by Ives and Johnsrud[13] in the case of pure potassium metal, is to consider a possible change in work-function of the photo-active material. There is evidence of the formation of thin metallic films on the surface of heated oxide-coated filaments. Case[7] has stated that in heating an oxide the pure metal is to some extent set free. J. E. Harris[14] has found that if an oxide-coated platinum filament is glowed in air, some of the platinum

[11] A. Ll. Hughes, Bull. Nat. Res. Council **2**, 10, 92 (1921).
[12] H. E. Ives, J.O.S.A. **8**, 580 (1924).
[13] H. E. Ives and A. L. Johnsrud, J.O.S.A. **11**, 579 (1925).
[14] J. E. Harris, Phys. Rev. **24**, 679 (1924).

enters into chemical combination with the oxides of the coating. If then the filament is glowed in vacuum, the platinum is liberated from the oxide, but remains in the coating in a finely divided state. There is evidence, then, that metal in a pure state may be present in the oxide coating of a filament.

Koller[15] expressed the belief that this metal formed a film over the oxide and was the source of the thermionic emission. The effect of very high temperatures was to partly destroy this film, and consequently decrease the electronic emission; but that subsequent reduction to normal temperatures renewed the metallic film and restored the thermionic emission to its original value.

In the experiments at hand it is quite possible that the photo-electrons come from just such a thin metallic film, and for such a film, it is not difficult to conceive of a value of the work-function much less than for an appreciable thickness of the same metal. It has been definitely found by Koppius[16] that the work-function for oxide-coated platinum decreased with increase of temperature, whereas for plain platinum it was practically constant at 4.80 volts (corresponding to a long wave-length limit $\lambda 2571$).

In direct agreement with this are the observations already described; namely, that large light-induced currents were found only when oxide-coated filaments were used. To account for the maximum observed in the current-voltage curve, it would be necessary to extend this reasoning to the effect that the applied potential in some way changes the work-function of the light-active film. It has been suggested to me by Dr. Millikan that this change may be brought about by the fact that new gases appear because of bombardment and change the work function of the filament.

Although it has been shown that the space-charge alone is not the source of the photo-electrons, it may be that the gradual decrease of the space charge with increase of potential alters the work-function of the metallic film in such a manner as to give rise to the maximum in the current-voltage curve.

This investigation was commenced at the Johns Hopkins University and completed at the Naval Research Laboratory. I am very grateful to Dr. A. Ellett for valuable aid and many generous suggestions. I am indebted to Dr. R. W. Wood, Dr. A. H. Pfund, and Dr. E. O. Hulburt for their interest.

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WASHINGTON, D. C.
September 8, 1926.

[15] L. R. Koller, Phys. Rev. **25**, 671 (1925).
[16] O. Koppius, Phys. Rev. **17**, 395 (1921).