ELECTRONIC DISCHARGE FROM COLD WIRES IN INTENSE ELECTRIC FIELDS

By Robert J. Piersol

Abstract

Measurements were obtained for cold electronic currents at a pressure of 10^{-8}mm, using thoroughly outgassed electrodes made of a minimum amount of metal. A silver plated glass cylinder served as an anode, with a coaxial tungsten filament cathode. Pure tungsten was used to avoid the changing surface conditions incident to outgassing thoriated tungsten. The gradient necessary for a given current was increased more than three fold by heating the filament for three hours at 2700°K, the approximate period necessary for maximum gradient. The type of current-gradient curve at room temperature verifies the observations of Millikan and Eyring.

Effect of temperature on the discharge of electrons from wires in intense electric fields has been extended by a study of the current-gradient relationship at liquid air temperature. These results show an intrinsic cold electronic phenomenon, possessing a type of current-gradient curve which has characteristics independent of temperature from 90°K to 1000°K.

I. Introduction

Wood[1] found that electrical conduction starts at one volt across an air gap, 4×10^{-3} cm in width, for ruled speculum metal on quartz. He attributed this to an atmosphere of negative electrons. Broxon[2] tested this theory, using two semi-transparent surfaces of such difference in curvature as to give Newton rings which could be used to measure the distance by interference. He found no disruptive discharge at a 5×10^{-5} cm gap, with an applied voltage producing a gradient of 6.4×10^5 volts per cm. Hoffman[3] used a vacuum as high as 1×10^{-3} mm. He found that with a gap distance of 4.2×10^{-5} cm, measured by interference, a gradient of 4.8×10^6 volts per cm was required for conduction. Thus the work of Broxon and Hoffman disproved the negative electron atmosphere theory. In order to account for electronic discharge due to intense electric fields, Schottky[4] set forth a theory based on the thermodynamic agitation of free electrons in a metal. The free electrons are shot out to very small distances from the surface of the metal, the distances depending on the Maxwellian distribution of velocities among the free electrons in the metal. In the absence of intense fields these electrons are attracted back into the metal by their electrical image; but if the field is sufficiently intense (of the order of 10^8 volts per cm) the applied field is greater than the image field, thereby pulling the electrons

[1] Wood, Phil. Mag. **24,** 316 (1912).

[2] Broxon, Phys. Rev. **20,** 476 (1922).

[3] Hoffman, Zeits. f. Physik **4,** 363 (1921); **5,** 109 (1923); Vehr. d. Deutsch Phys. Ges. **12,** 880 (1910); Phys. Zeits. **11,** 961 (1910); **13,** 480 (1912); **13,** 1029 (1912); Ann. d. Physik **42,** 1196 (1913); **52,** 665 (1917).

[4] Schottky, Jahrb. d. Radioakt. **12,** 200 (1915); Zeits. f. Physik **14,** 80 (1923; **15,** 63 (1923).

away from the metal. Millikan and Shackelford,[5] for two intreated crossed tungsten wires, found the first leak between 1×10^5 and 5×10^5 volts per cm. After heating the tungsten wires at a temperature of 2700°K, the first leak was pushed up to 4.3×10^6 volts per cm. Later Millikan and Eyring[6] used a fine thoriated tungsten filament waxial to a copper cylinder. Outgassing the filament at 2300°K produced a critical potential gradient as high as 7.4×10^5 volts per cm. The current was found to be completely independent of temperature up to 800°C. The writer[7] found a critical gradient of 5.4×10^6 volts per cm between electrodes made from molybdenum plates pressed into hemispherical shells, outgassed at 1400°C by induction heating; this being the highest critical gradient thus far reported. Lilienfeld[8] has used a pointed cathode in a high vacuum x-ray tube. He ascribes the emission as due to the direct action of the applied field on the sharply curved end of the cathode. Unpublished work by Rentschler showed that the normal operation of the Lilienfeld tube is not due to the pulling of the electrons directly out of the metal; but is caused by ionization either from residual gases or impurities pulled from the surface of the electrodes. Nevertheless Rentschler expressed conviction that electrons may be pulled out of pure metals provided the field is sufficiently intense. Hayden[9] found a critical gradient of 1.3×10^6 volts per cm, using outgassed molybdenum spheres 0.306 cm apart. The writer[10] found that the critical gradient between molybdenum electrodes may be increased from 1.2×10^6 to 5.4×10^6 volts per cm by outgassing the electrodes. Preliminary work seemed to indicate that an increase of temperature, up to the thermionic range, influenced both the current and the breakdown voltage. Further investigation showed that this apparent change was due largely to occluded gases diffusing to the surface of the electrodes at higher temperatures. Dushman[11] found a constant ratio between the logarithm of the current and the square root of the plate voltage, for a temperature range between 1470°K and 2239°K, and for plate potentials from 100 to 475 volts. This is in accordance with the theoretical deductions of Schottky. Gossling,[12] in a very extensive research, has shown in a qualitative manner the reality of cold electronic discharge. The results are completely inconsistent with the Schottky variation of current with temperature. Working under Swann, del Rosario[13] obtained results, which he interpreted as casting doubt on the conclusions of previous observers that the currents they obtained were due to the pulling of electrons from the metal surfaces. He interpreted his observations as showing that the effect is due to voltage

[5] Millikan and Shackelford, Phys. Rev. **15**, 239 (1920).

[6] Millikan and Eyring, Phys. Rev. **27**, 51 (1926).

[7] Piersol, Report Brit. A. A. S. p. 359 (1924).

[8] Lilienfeld, Phys. Rev. **2**, 1350 (1921); Akad. d. Wiss. **62**, 31 (1920); Vehr. d. Deutsch Phys. Ges. **2**, 13 (1921); Phys. Zeits. **20**, 280 (1919); **23**, 506 (1922).

[9] Hayden, Jour. A. I. E. E. **41**, 854 (1922).

[10] Piersol, Phys. Rev. **25**, 113 (1925).

[11] Dushman, Phys. Rev. **25**, 338 (1925).

[12] Gossling, Phil. Mag. **1**, 606 (1926).

[13] del Rosario, J. Franklin Inst. **203**, 243 (1927).

rather than field gradient, thereby concluding that the currents observed by Millikan and Eyring might possibly be due to ionization of residual gases in the space between the anode and cathode.

II. Apparatus and Method

The type of tube used, as shown at T in Fig. 1, was made of Corning G702P glass (similar to Pyrex) to permit baking out at 500°C. The filament, 2.92×10^{-3} cm in diameter, was of pure tungsten (non-thoriated), thereby permitting outgassing at 2700°K, without the change of surface conditions due to the diffusion of thorium to the surface. The filament G was suspended by tungsten leads through seals at D and E, being held taut by a helical tungsten spring F. The inside of the tube was silver-plated between the

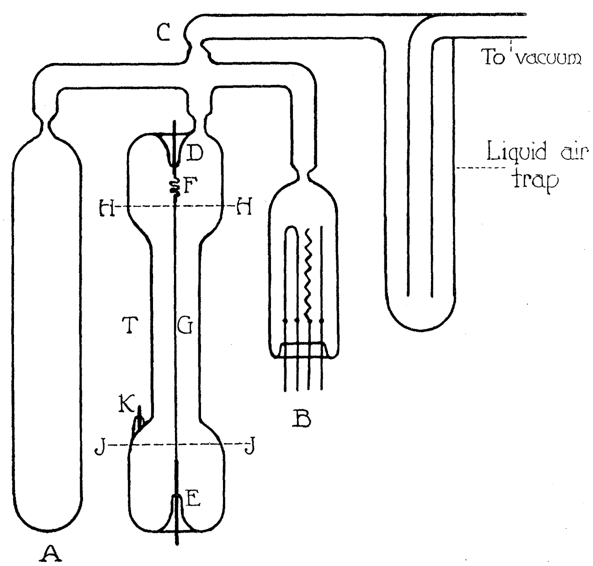

Fig. 1. Tube and exhaust system.

plane HH and the plane JJ. This silver plate on the restricted area of the tube served as an anode, 2.16 cm in diameter, being connected electrically to the tungsten electrode which was sealed in at K. The silver, being of semi-transparent thickness, was far more readily outgassed than a relatively heavy copper cylinder as used by Millikan or nickel cylinder as in the experiment of del Rosario.

As shown in Fig. 1, to the cold electronic tube there was attached a charcoal tube A and a Dushman ionization gauge B, assembled from metal parts of a UX200 radio tube.

Modern high vacuum technique was employed. The tubes were thoroughly outgassed by baking, inductive heating, and bombarding, while the filaments were heated at 2700°K. After evacuation the tubes were sealed off from the system at C, the charcoal tube being submerged in liquid air continuously until the completion of the experiment. The vacuum remained remarkably constant, being of the order of 10^{-8} mm.

Although this work was completed before the publication of the article by Gossling, identical high tension circuits were used to supply rectified alternating current. Sufficient smoothing capacity was added to reduce the cycle voltage variation to less than one percent when discharging one milliampere. Very exact voltage readings were obtained, by a Shrader electrostatic voltmeter.

III. Experimental Results

For a tungsten filament, 0.00146 cm radius, coaxial to a cylindrical anode, 1.06 cm radius, it may be calculated that the field strength (in volts per cm) at the surface of the filament is 103 times the difference of potential between the electrodes.

As noted by Millikan and Gossling, in the case of wires that have been subjected to extreme heat treatment, sufficiently high gradient may produce a rupture of the surface of the wire, causing the current to jump instantly a thousandfold. In the present experiments this occurred at a gradient necessary to draw a cold electronic current of approximately one milliampere. The resulting conical stream of electrons caused a fluorescent spot to occur, removing the silver from a small area of the glass in a few seconds. This electron stream could be deflected by a magnet. The surface rupture of the wire could be healed by heating the wire for several hours at 2700°K. The rupture of the surface of a filament caused fluctuating current at lower gradients. Therefore all the results reported in this article were obtained for wires where the tube showed no fluorescence in a darkened room. A tube with a ruptured filament was discarded as worthless for reproducible results. Even when reconditioned by heat treatment the tube was not as satisfactory as a new tube.

In all observations the filaments were conditioned, previous to recording data, by drawing a cold electronic current for several minutes at a gradient greater than that to be used. This is because results for decreasing voltages duplicate those for increasing voltages only over a range lower than the conditioning voltage.

In all, 14 tubes were made and used. The results were very uniform from tube to tube. Although 33 sets of observations were obtained, the results may be summarized in three groups showing, first, curves for observations at room temperature for the filament previous to heating; secondly, curves for observations at room temperature for a filament that had been outgassed at 2700°K; and thirdly, curves for observations at liquid air temperature for an outgassed filament. Each curve represents a single set of readings, both for increasing and decreasing voltage, in which the values have not been weighted.

Fig. 2 shows the relation between the logarithm of the current and the potential gradient previous to the heating of the filament at a pressure of 10^{-8} mm as measured by an ionization gauge. Fig. 3 emphasizes the effect of outgassing the filament at 2700°K for three hours. It should be noted that the gradient necessary to give a cold electronic current of 1×10^{-7} amperes has increased from 4.4×10^5 volts per cm to 1.5×10^6 volts per cm.

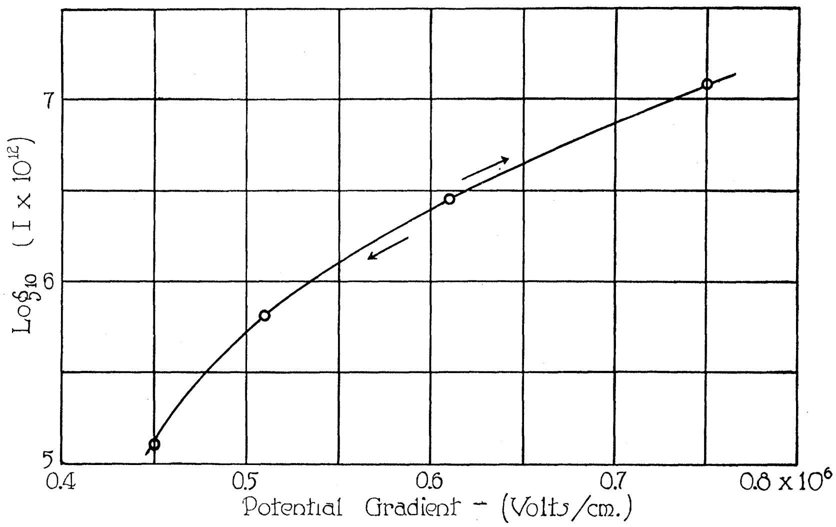

Fig. 2. Relation between the logarithm of the current and the potential gradient before outgassing. Readings taken at 300°K.

At 1×10^{-5} amperes it has increased from 7.3×10^5 volts per cm to 2.2×10^6 volts per cm. This shows that it requires over three times the gradient to

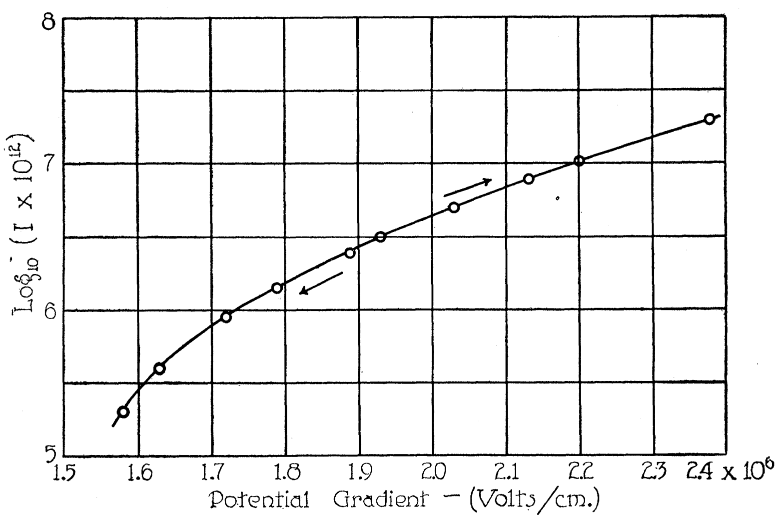

Fig. 3. Relation between the logarithm of the current and the potential gradient after outgassing. Readings taken at 300°K after outgassing at 2700°K for three hours.

give a cold electronic current from an outgassed metal equal to that from the same metal previous to outgassing.

Filaments were outgassed at 2700°K for periods as long as 48 hours. Results showed that there was no appreciable increase in gradient due to outgassing at 2700°K for a length of time longer than three hours.

IV. Influence of Temperature

Fig. 4 gives results when the entire tube was held at a temperature of −180°C. This was done by submerging the cold electronic tube in a large necked thermos bottle filled with liquid air. The liquid air itself is a sufficiently high insulator to prevent measurable leakage except at the frosted area where the leads came out, at which point they were insulated by glass tubing.

The characteristics of this curve are similar to those for an outgassed filament at room temperature. In this particular case the filament had been

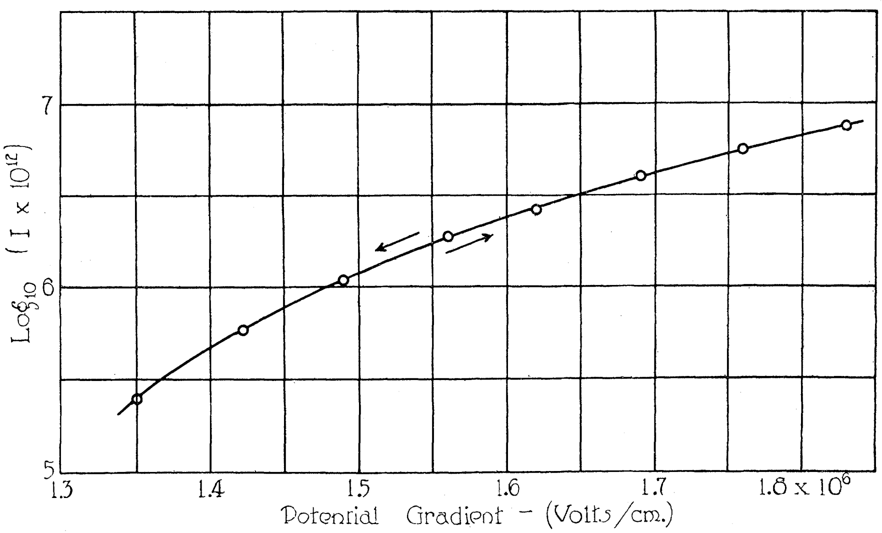

Fig. 4. Relation between the logarithm of the current and the potential gradient at low temperatures. Readings taken at −180°C after outgassing at 2700°K for one hour.

outgassed at 2700°K for a period of one hour as compared to three hours for the filament shown in Fig. 3. Therefore the gradient necessary to produce a certain current was somewhat less. So far as known, these are the first results to be published for liquid air temperature. A series of results on filaments that had been well outgassed showed that observations gave the same characteristic current-voltage curve when the filament was at temperature as high as 1000°K.

V. Discussion

The fact that the Schottky linear relation between the logarithm of the current and the square root of the field gradient does not hold is shown by replotting the previous results. In Fig. 5 curve *A* shows the results at room temperature for a filament prior to outgassing; curve *B*, the results at room temperature for a filament outgassed three hours at 2700°K; and curve *C*, the results at liquid air temperature for a filament outgassed one hour at 2700°K. Instead of a straight line the curves are continually concave toward the gradient axis. This is precisely the result found by Millikan.

After the experimental results were recorded, it was discovered that these observations, as well as those of Millikan, satisfy a very simple numerical equation, which may be interpreted in terms of the applied field necessary

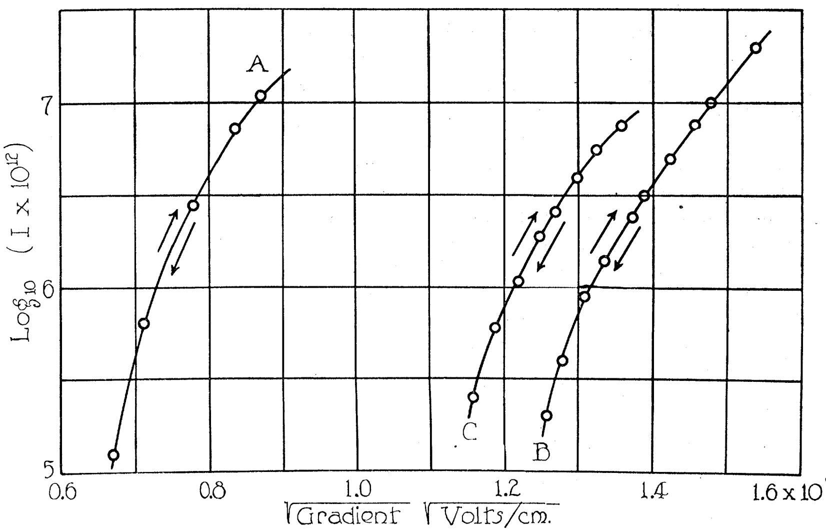

Fig. 5. Relation between the logarithm of the current and the square root of the potential gradient. A refers to Fig. 2, B to Fig. 3 and C to Fig. 4.

to cause the ejection of an electron from its orbit, by overcoming the orbital quantum energy. This theory and its verification by the results of Millikan and the writer will be given in a forthcoming article which is now ready to be presented for publication.

The larger part of the experimental observations were made in the Westinghouse Research Laboratory, prior to the time of the writer left the company. Also acknowledgment of criticism assistance is given to Dr. Slepiam, Dr. Kahler, Mr. Smede, and Mr. Rashevsky.

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