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The Effect of High Electrostatic Fields on the Conductivity of Tungsten

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A grounded tungsten wire (0.0078-mm diameter) was mounted coaxially with a cylinder which was made negative relative to the wire, and a difference of potential was applied between the cylinder and the wire. The procedure consisted of measuring the resistance of the tungsten wire first without an electric field and then with a field. With a vacuum of about 10^{-6} mm Hg and with fields of about 10^6 v/cm, measurements showed that: (1) An increase in resistance always resulted with the application of the field; (2) the change was different for different temperatures of the filament and for different vacuum conditions; (3) no measurable change occurred unless the field exceeded a certain value; (4) a small leakage or ionization current was associated with the changes in resistance. The observed changes might have been caused by: (1) leakage current, (2) ionization current, (3) radial stress in the wire resulting from the high field, or (4) other reasons. Calculations showed that reasons (1) and (3) produce changes much smaller than those observed and that the results are explainable wholly by reason (2) if it is assumed that most of the ionization occurs near the surface of the wire.

I. INTRODUCTION

PERKINS[1] in 1921 and again in 1925[2] observed that gold and bismuth exhibited an increase in resistance in the presence of an electrostatic field. M. Pierucci,[3] M. Perucca,[4] and R. Deaglio[5] have observed changes in resistance of thin, metallic films deposited on quartz or glass upon application of a field. Their results indicate that there is a decrease in resistance upon applying a field. In work on the effect of high electrostatic fields upon the vaporization rate of metals A. G. Worthing[6] and G. B. Estabrook[7] observed changes in resistance upon applying high fields. Worthing observed that there was a sudden decrease in the resistance of a tungsten wire upon applying a field and a sudden increase upon removing the field. Estabrook also observed this effect for the case of platinum and molybdenum, but the effect was opposite to that found by Worthing.

The present research was undertaken to obtain quantitative results on the effect of high electrostatic fields on the electrical resistance of small tungsten wires.

II. APPARATUS

The tungsten[8] used was in the form of a wire 0.00078 cm in diameter. This value measured by a microscope checked well with that obtained with the value 0.18 mg per 200-mm length furnished by the manufacturer. Figure 1 shows a cross-sectional view of the apparatus used. Approximately a 10-cm length of this wire was mounted coaxially with respect to a cylinder. The two springs *S* made of 5-mil Kovar were used to keep the wire under slight tension. To facilitate centering, holes (0.29-mm diameter) were drilled along two diameters approximately at right angles to each other at the ends and also at the center of the cylinder. The wire was centered by means of the adjusting screws *A* at each end. The rings *N*, holding the adjusting screws, were grounded and served as guard rings. The ends of springs *S* were threaded through short glass capillaries encased in the plates at each end, and the tungsten wire was soldered onto the ends of the Kovar springs. Although solder does not adhere to tungsten, it made a good mechanical and electrical joint as long as the filament was not heated to a very high temperature. The cylinder and the rings were supported by glass rods and the entire assembly introduced into a glass tube connected

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[1] H. A. Perkins, Phys. Rev. **18**, 131 (1921).
[2] H. A. Perkins, Phys. Rev. **25**, 584 (1925).
[3] M. Pierucci, Nuovo Cimento **9**, 33–42 (1932).
[4] M. Perucca, Comptes rendus **198**, 456 (1934).
[5] R. Deaglio, Nuovo Cimento **11**, 288 (1934).
[6] A. G. Worthing, Phys. Rev. **17**, 418 (1921).
[7] G. B. Estabrook, Ph.D. Thesis, University of Pittsburgh (1932).
[8] Furnished by the General Electric Company, Lamp Development Division, Nela Park, Cleveland, Ohio.

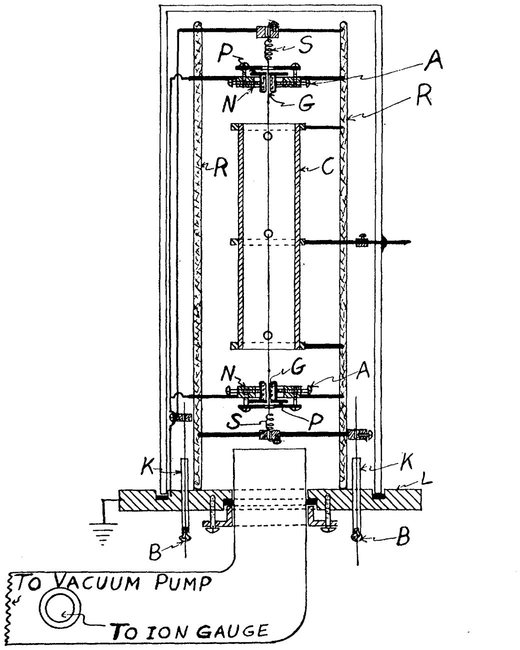

FIG. 1. Cross-sectional view of apparatus. *A*, adjusting screws; *B*, glass beads; *C*, cylinder; *G*, glass capillary; *K*, Kovar tubes; *N*, guard rings; *P*, adjustment plate; *R*, glass rods; *S*, springs; *L*, brass plate ($\frac{3}{5}$ normal size).

to a mercury diffusion pump.[9] For ease in replacing filaments, the glass tube rested on a rubber gasket in a groove of the brass plate *L*. The electrical connections were brought to the outside through two Kovar tubes *K* soldered onto the brass plate. The ends of the tubes were sealed with glass beads *B* which made vacuum seals and insulated the wires from the plate. A No. 46 radio tube served as an ion pressure gauge. A Kohlrausch bridge was used for measuring resistances. Changes in resistance were measured by the galvanometer deflection from the balanced position, galvanometer deflections being previously calibrated in terms of resistance changes. All lead wires and instruments were shielded and grounded. The galvanometer of the Kohlrausch bridge circuit was introduced into the ground circuit in order to detect and measure any "leakage" current.

High voltages for obtaining the fields between the cylinder and wire were produced by an x-ray transformer and a Kenotron KR-3 rectifier. The negative side of the line was connected to the cylinder in the tube and the positive side was grounded at the transformer. The tungsten wire was also grounded.

III. PROCEDURE AND RESULTS

The tungsten wire was well centered along the axis of the cylinder, and the entire assembly (see Fig. 1) was then inserted in the tube connected to the vacuum pump. The tube was outgassed by heating it locally with a gas flame, and all measurements were taken with a vacuum of about 10^{-6} mm Hg. Previous to making measurements with the wire in the electrostatic field, the variation of resistance with current through the wire was measured with increasing and decreasing currents (Fig. 2). This was necessary in order to calculate changes in resistance resulting from a change in current in the circuit in which only the resistance of the tungsten wire would vary as occurred in the course of measurement. The relation is practically linear. Measurements were made after the filament had been heated for about 10 minutes at the highest temperature always below incandescence. The wire was not "well aged;" nevertheless, it behaved in a reproducible and consistent manner. Throughout, the current was measured to the nearest 0.0001 ma by means of a carefully adjusted potentiometer. The temperature of the wire was calculated from a temperature-resistivity calibration.

The deflections of the galvanometer in the Kohlrausch bridge from a balanced position were calibrated in terms of changes in resistance. For the most sensitive conditions, a deflection

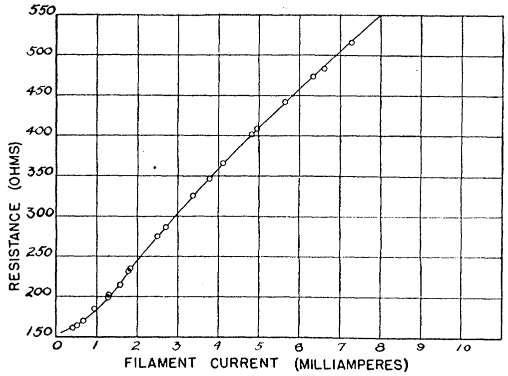

FIG. 2. Variation of resistance with current for an unaged tungsten filament. Diameter 0.00078 cm, length 10.38 cm.

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[9] Built by R. Nestler at the Bartol Foundation.

of one division represented a change in resistance of 0.0015 ohm in 500 ohms. A deflection of 0.1 division could be estimated so that it was possible to detect a change of 3 parts in 10,000,000.

The negative side of the high voltage source was then connected to the cylinder, and the tungsten wire was grounded at the galvanometer connection of the bridge. Because of the smallness of the wire, a relatively small difference of potential gave rise to a high field strength at the surface of the wire. For example, a difference in potential of 10,000 volts between the wire and cylinder gave rise to a surface field strength of 3.35×10^6 v/cm. Measurements of changes in resistance with applied fields were made on numerous tungsten wires. The results for one particular wire are shown in Fig. 3. It shows that there was always an increase in resistance with the application of an electric field provided the field exceeded a certain value below which no change could be detected. The magnitude of the change for a particular field strength depended on the temperature of the filament and upon vacuum conditions. The results on the other tungsten filaments were similar. The maximum observed changes are shown in Table I.

No change of resistance was observed until a surface field strength of 0.75×10^6 v/cm was reached for the filament at 20°C and the value at which any change was observed increased as the temperature of the filament increased. The field strengths at which a change was first observed for the various temperatures and vacuum conditions are shown in Table II.

When the galvanometer of the bridge was moved to the ground circuit, it measured any leakage current passing to ground. The measured results are shown in Fig. 4. The maximum deflection was never more than 2 divisions at 100 cm and represented a current of approximately 3×10^{-8} amp. The deflection appeared immediately as soon as the field was applied. As Fig. 4 shows, the current varied with the temperature of the filament and also with the vacuum much in the same way as did the changes in resistance. If the field was kept constant and the temperature was changed from one value to another, there was a change in the leakage current. There was an increase if the change was one from a high temperature to one of a low temperature, and a decrease if the reverse change was made, the increase and decrease always being the same. Also the final leakage current was the same as that found by suddenly applying the field. However, when the temperature of the wire was changed suddenly from a low temperature to a high, there was a sudden decrease in leakage current, but when the temperature was changed from a high to a low value, the current increased very slowly, possibly in consequence of the very slow adjustment to a new temperature equilibrium.

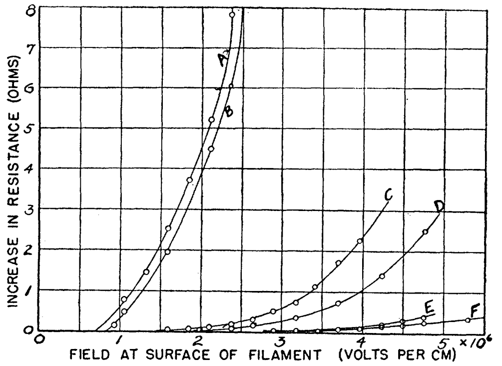

FIG. 3. Change in resistance with applied field of unaged tungsten. Curves *A*, *C*, *E* for pressure 3×10^{-6} mm Hg. Curves *B*, *D*, *F* for pressure 8×10^{-7} mm Hg. Curves *A* and *B*—$R=157.3$ ohms, $T=20$°C. Curves *C* and *D*—$R=323.9$ ohms, $T=280$°C. Curves *E* and *F*—$R=514.7$ ohms, $T=580$°C.

TABLE I. Maximum observed change in resistance of tungsten wire at various temperatures with field strength at surface of wire.

Temp. of wire °C	Max. observed change, ohms	Percent change	Field strengths 10^6 v/cm
	Vacuum 3×10^{-6} mm Hg		
20	13.8	8.8	2.90
280	2.3	0.71	3.97
580	0.37	0.072	4.77
	Vacuum 8×10^{-7} mm Hg		
20	13.5	8.7	3.18
280	2.5	0.77	4.77
580	0.34	0.066	5.31

IV. DISCUSSION

Measurements with high electrostatic fields at the surface of the tungsten wire showed that the wire exhibited increases in resistance with applied fields. The magnitude of the changes

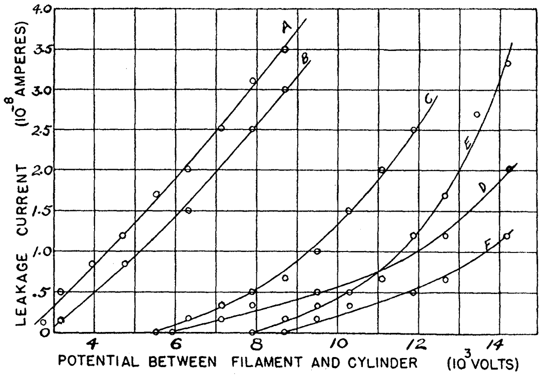

FIG. 4. Variation of leakage current with potential. Curve designations same as for Fig. 3.

depended on the temperature of the wire and on the vacuum conditions. Associated with these changes was a leakage current which varied with the temperature of the wire and vacuum conditions much in the same manner as did the changes in resistance.

The changes in resistance that resulted with the application of high fields might have been due to several reasons:

1. Leakage current passing through the filament, thus heating it and increasing its resistance.
2. Ionization current in the space between the wire and the cylinder passing to the filament, thus heating it and increasing the resistance.
3. Radial stress in the wire resulting from the high electrostatic field.
4. Others.

Simple calculations show that changes due to reasons 1 and 3 are much too small to account for the measured changes in resistance. The fact that the leakage current measured varied with the temperature of the wire and with vacuum conditions suggests that it might be an ionization current. That this is possible at pressures of 10^{-6} mm Hg or better is the basis of all ionization pressure gauges.

If an electron is generated in the gas in the cylinder by photons, γ-rays, or cosmic rays, it will move toward the wire and at some appropriate distance will start to ionize by collision. The negative ions formed will move in toward the wire and the positive ions will move outward to the cylinder. It has been shown by Dempster,[10] Loeb,[11] and Druyvesteyn and Penning[12] that positive ions of sufficient energy striking the cylinder would liberate electrons from it. These electrons would then move toward the wire and produce more ions by collision. Regarding electron emission from the cathode by positive ions, Loeb quotes: "Concerning this process much information is at hand, though none is satisfactory owing to the impossibility of producing or studying reproducible surfaces."[13] A steady current will occur (neglecting ionization by outside sources) when the total number of positive ions produced by a primary electron will eject one electron from the cylinder. The number of extra electrons liberated from the cathode per ion formed between the electrodes is not known for different electrodes[14] at such high ratios of field strength to pressure as used in the course of these measurements, so that a quantitative discussion of this is not possible here. A complete and detailed discussion of what occurs between concentric cylinders at low pressures and high field strengths is complicated by impurities and general conditions in the tube.[15] Quoting from Loeb: "In tubes at very low pressures, 0.01 mm, the character of the gas becomes somewhat doubtful, for adsorbed gases coming from the walls and electrodes, whose nature is unknown, begin to play an important role. Below 10^{-5} mm the gas present is completely indeterminate."[16]

An ionization current would therefore consist of a migration of electrons or negative ions toward the wire and positive ions toward the cylinder. The energy of the electrons in passing through a potential difference in the cylinder

TABLE II. Field strengths at surface of tungsten wire at which a change in resistance was first observed.

Temp. °C	Field strength 10^6 v/cm	
	(Vac. 3×10^{-6} mm Hg)	(Vac. 8×10^{-7} mm Hg)
20	0.75	0.80
280	1.3	1.7
580	2.5	3.3

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[10] A. J. Dempster, Phys. Rev. **46**, 728 (1934).

[11] Leonard B. Loeb, *Fundamental Processes of Electrical Discharges in Gases* (John Wiley and Sons, New York, 1939), pp. 377, 480.

[12] M. J. Druyvesteyn and E. M. Penning, Rev. Mod. Phys. **12**, 98, 107 ff. (1940).

[13] Leonard B. Loeb, reference 11, p. 378.

[14] M. J. Druyvesteyn and F. M. Penning, reference 12, p. 106 ff.

[15] Leonard B. Loeb, reference 11, p. 451.

[16] Leonard B. Loeb, reference 11, p. 480.

would be transferred to the wire, heating it and therefore increasing its resistance. To calculate what changes in resistance such assumed ionization current would produce, Fig. 5 was drawn showing the variation of resistance of the wire with power (I^2R) input. The slope of this curve was taken at the experimental values of resistance. The product of this slope and a power determined as dissipated because of ionization currents and transferred to the filament would give the expected change of resistance for the filament on the application of the high electrostatic field. Since the ionization current consists of a stream of negative ions in one direction and an equal number of positive ions in the opposite direction, depending on their place of origin, one might expect something on the order of one-half of the calculated ionization power to be transferred to the wire. The changes that would result if exactly half of the power were transferred to the wire are shown as ΔR_p in Tables III and IV.

TABLE III. Comparison of measured changes in resistance with computed changes assumed to be due to ionization power. Vacuum 3×10^{-6} mm Hg.

R_x ohms	Temp. °C	E 10^6 v/cm	ΔR_x ohms	ΔR_p ohms	$\frac{\Delta R_p}{\Delta R_x}$
514.7	580	2.9	0.0068	0.043	6.3
		3.18	0.013	0.090	6.9
		3.44	0.026	0.15	5.8
		3.71	0.069	0.22	3.7
		3.97	0.14	0.41	2.9
		4.24	0.18	0.63	3.5
		4.50	0.28	1.05	3.7
		4.77	0.37	1.37	3.7
323.9	280	1.59	0.024	0	0
		1.85	0.045	0	0
		2.12	0.10	0.11	1.1
		2.38	0.17	0.23	1.4
		2.65	0.29	0.39	1.3
		2.91	0.48	0.57	1.2
		3.18	0.72	0.93	1.3
		3.44	1.11	1.51	1.4
		3.71	1.71	2.18	1.3
		3.97	2.26	2.92	1.3
157.3	20	0.93	0.13	0.56	4.3
		1.06	0.76	1.9	2.5
		1.33	1.44	4.0	2.8
		1.59	2.51	6.8	2.7
		1.85	3.7	11.3	3.0
		2.12	5.2	15.2	2.9
		2.38	7.8	21.5	2.8
		2.65	10.8	30.5	2.8
		2.91	13.8	36.6	2.7

R_x = Resistance of wire; E = Field strength at surface of wire; ΔR_x = Measured change in resistance due to field; ΔR_p = Calculated change in resistance from ionization power; $(\Delta R_p/\Delta R_x)$ = Ratio of measured change to calculated change in resistance.

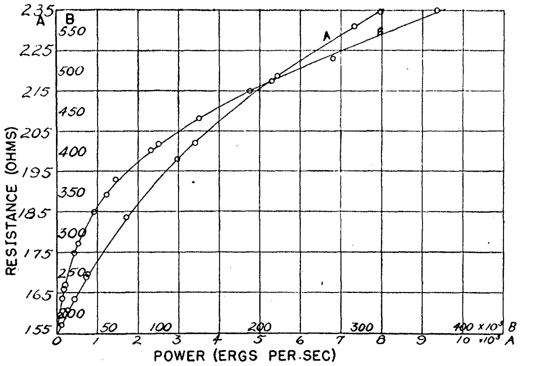

FIG. 5. Variation with power input of resistance of an unaged tungsten filament. Diameter—0.00078 cm, length—10.38 cm.

Comparing the calculated with the observed changes in resistance, it is seen that the computed effects for the observed ionization currents account for more than the observed changes in resistance. The ratios of the calculated changes to the observed are shown also in Tables III and IV.

The ratios of calculated changes to the observed changes for a particular temperature of the filament remain practically constant at different field strengths. The ratios, however, are different for different temperatures of the filament. These results are compatible if the assumption is made that there exists a region of greater density of gas molecules near the surface of the wire than anywhere else inside the cylinder and that the density of the gas near the surface of the wire is decreased when the temperature of the filament is increased. This could well be in the form of adsorbed gas on the surface of the tungsten. This assumption is reasonable because of the high field strength and the large gradient of the radial field existing there. Because of this greater density near the surface of the wire, a large part of the ionization by collision is assumed to occur in this region. Hence, the electrons or negative ions would not pass through the potential difference applied, but would pass through a smaller potential difference, and the energy transferred to the wire per second would be smaller.

By taking the requisite potential difference to give the measured changes in resistance, the distance from the surface of the wire giving this

TABLE IV. Comparison of measured changes in resistance with computed changes assumed to be due to ionization power. Vacuum 8×10^{-7} mm Hg.

R_x ohms	Temp. °C	E 10^6 v/cm	ΔR_x ohms	ΔR_p ohms	$\frac{\Delta R_p}{\Delta R_x}$
513.4	580	3.18	0.011	0.046	4.2
		3.44	0.034	0.10	2.9
		3.97	0.093	0.17	1.8
		4.24	0.130	0.25	1.9
		4.50	0.162	0.26	1.6
		4.77	0.246	0.49	2.0
		5.31	0.339	0.69	2.0
322.6	280	1.99	0.018	0	0
		2.38	0.067	0.12	1.8
		2.65	0.14	0.26	1.9
		3.18	0.35	0.47	1.3
		3.71	0.71	0.73	1.0
		4.24	1.40	1.5	1.1
		4.77	2.50	2.8	1.1
156.1	20	0.93	0.14	0	0
		1.06	0.47	0.4	1.4
		1.59	1.94	4.8	2.5
		2.12	4.48	11.4	2.6
		2.65	9.13	23.7	2.6
		2.91	13.5	31.2	2.3

R_x = Resistance of wire; E = Field strength at surface of wire; ΔR_x = Measured change in resistance due to field; ΔR_p = Calculated change in resistance from ionization power; $(\Delta R_p/\Delta R_x)$ = Ratio of measured change to calculated change in resistance.

potential difference can now be calculated. The potential at a distance r from a grounded cylinder of radius a having a charge q per unit length inside another cylinder of radius b is given by the relation

$$V_r=-2q\ln(r/a). \tag{1}$$

If the potential is to be a fraction of the applied potential, say ${}_fV_b$, then

$$\frac{V_b}{{}_fV_b}=\frac{-2q\ln(b/a)}{-2q\ln(r/a)}=\frac{1}{f}=\frac{\ln(b/a)}{\ln(r/a)}, \tag{2}$$

from which is obtained

$$r=a(b/a)^f. \tag{3}$$

Substituting the values for a and b one obtains

$$r=0.0039\text{ mm}\left(\frac{8.2}{0.0039}\right)^f.$$

The average value for f when the wire was at 20°C, pressure 3×10^{-6} mm Hg, is (1/2.8) and leads to 0.06 mm for the value of r. This distance is 7.3×10^{-3} of the radius of the cylinder or a distance 15 times as great as the radius of the wire. This value of r would indicate that most of the ionization occurs in a volume of 1.1×10^{-2} mm^3 per unit length of the wire or 5.4×10^{-5} of the total volume. The value of r when the filament was operated at 280°C, vacuum 3×10^{-6} mm Hg, was 1.4 mm or 0.17 of the radius of the cylinder. The ionization occurred inside a volume 6.2 mm^3 per unit length of wire, or 0.029 of the total volume. This value for r at 280°C was larger than the value at 20°C. This is in agreement with the assumption made, namely, that as the temperature of the filament is increased, the density of the molecular cloud around the filament decreases. The ionization would be expected to occur, therefore, at the higher temperature throughout a larger volume and to be smaller for a given voltage applied between wire and cylinder. The value for r at 580°C should be larger than at 280°C, and the ionization should be less for any given voltage applied. However, the ionization current at the highest temperature was found, as expected, to be smaller than at the lower temperatures, but the value of r, contrary to expectations, was smaller than the value for r at 280°C. To check with what was expected, the leakage current should have been very much smaller. A larger ionization current than expected might have resulted from several reasons: (1) The filament might have liberated adsorbed gases at the higher temperature; (2) A noticeably greater part of the ionization current at the high temperatures was leakage surface current because of the higher voltages at which the data for the high temperatures were taken (see Fig. 3 and Tables III and IV).

The values of r calculated for various conditions are shown in Table V. As has been mentioned, the results depend considerably on the impurities present and the nature of the cathode surfaces.

TABLE V. Values of radii inside which most of the ionization occurs.

R_x ohms	Temp. °C	r mm	r mm
		(Press. 3×10^{-6} mm Hg)	(Press. 8×10^{-7} mm Hg)
514	580	0.04	0.22
323	280	1.4	2.3
156	20	0.06	0.08

There are reasons to suspect[17] that the ionization may not occur in such large volumes as indicated in Table V. The results can be explained then if it is assumed that only a fraction of the measured ionization current passes through the potential difference applied between cylinder and filament. The mechanism can be viewed in this fashion. It is assumed that there exists adsorbed gases and/or adsorbed tungsten oxide at the surface of the tungsten filament. Suppose that by some means or other an electron is liberated at the inner surface of the cylinder, the cathode. The electron will be accelerated towards the filament and will ionize only when it strikes the adsorbed layer. There equal number of electrons and positive ions will be produced; the electrons passing through a very small potential difference to the filament while the positive ions are accelerated towards the cylinder by passing through the entire potential difference. The positive ions arriving at the cylinder will liberate more electrons and the same process repeated again. A steady current will result when the number of positive ions produced by one electron at the anode or filament will produce one electron at the cathode or cylinder.

Let the ratio $\Delta R_x/\Delta R_p$ as previously defined be designated by "f." To account for the measured change in resistance, ΔR_x, the number of electrons passing through the applied potential difference per second would have to be a fraction "f" of the measured number. One electron, then, on the average would produce $(1-f)/f$ positive ions at the filament and $(1-f)/f$ positive ions would in turn produce on the average one electron at the cylinder wall. The number of electrons per positive ion liberated at the cathode is known as an "alternative second Townsend Coefficient."[18] The value for this coefficient is given by the relation

$$\gamma = f/1-f.$$

Using the average values for $1/f=\Delta R_p/\Delta R_x$ found in Tables III and IV we find the values for γ at a pressure of 3×10^{-6} mm Hg to be 0.40, 3.3, and 0.55 for temperatures 580°C, 280°C, and 20°C, respectively, and at a pressure of 8×10^{-6} mm Hg, they are 1.1, 2.5, 0.66 at the same temperatures. These values are averages at a field strength to pressure ratio, E/P, of the order of 10^{12} v/(cm mm Hg). Other experimental values for γ are not available at such high ratios of E/P as used here so that no comparisons can be made here. It must be remembered that these coefficients apply only to the surfaces used for this investigation.

Variations in resistance with applied field might have resulted because of other reasons such as a change in emissivity or a structural change in the wire itself. These changes are entirely possible, but an explanation of the results wholly on these changes would not account for the effects of the ionization currents, and it is seen that these can account for the observed changes. To detect changes due to other assumed reasons, one would have to reduce ionization currents to negligible amounts, and this can be done only in a vacuum of 10^{-9} mm Hg or better.

ACKNOWLEDGMENTS

I wish to express my thanks to Dr. E. Hutchisson and to Dr. C. S. Smith. I am also grateful to Dr. A. G. Worthing for his many helpful suggestions.

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[17] W. P. Reid, Phys. Rev. **63**, 359 (1943).

[18] Leonard B. Loeb, reference 11, p. 687.