LAWS GOVERNING THE PULLING OF ELECTRONS OUT OF METALS BY INTENSE ELECTRICAL FIELDS

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Abstract

Current from thoriated tungsten filaments in vacuum, due to radial fields of up to two million volts per cm.—Three filaments were tested, each .00123 cm in diam. and suspended under tension in the axis of a copper cylinder of 1.6 cm diam. From the dimensions, the radial field at the surface of the filament was 228 times the applied potential difference. The electron currents pulled from the tungsten by the high fields (field currents) rise steadily from 10^{-12} to 10^{-3} amp. as the field is increased from about 400 to 1100 kv/cm. In the dark, luminous spots were seen on the anode, indicating that these currents come from a few active surface spots. The field current (for a given voltage) depends on the value of the maximum field current previously drawn from it (conditioning current), being reversibly reproducible below the conditioning current. The higher the conditioning current, the lower the field current. A previous heating to high temperatures (2400°C) decreases the field current and also decreases the slope of the current-voltage curve. Both effects (current and heating) show fatigue. *Variation with temperature of the filament, to* 800°C. The field currents are completely independent of temperature up to 700°, but a temperature of 800° increases the currents due to a given field when this is sufficiently large, by a factor which is roughly independent of the current (10^{-8} to 10^{-4} amp.). *Electron theory.* In explanation of these results, it is suggested that the field currents are due to conduction electrons pulled from minute peaks on the surface, the fatigue effects of both current treatment and heat treatment being due to the rounding off of these peaks by positive ion bombardment or by temperature. Chemical changes may also alter the surface. The lack of dependence of field currents upon temperature furnishes strong evidence that most of the conduction electrons do not share in the energy of thermal agitation. The thermions, however, do share in this energy; they are presumably responsible for the Peltier and thermo-electric effects. In this theory it is assumed that conduction electrons follow the same sort of quantum laws in their escape from the solid as do atoms of a light element at temperatures far below the boiling point.

I. Introduction

THE experiments of Earhart,[1] Kinsley,[2] Hobbs,[3] Hoffman,[4] and Lilienfeld,[5] a previous investigation by one of us,[6] and the theoreti-

[1] Earhart, Phil. Mag. **1,** 147 (1901); Phil. Mag. **16,** 147 (1908).

[2] Kinsley, Phil. Mag. **9,** 692 (1905).

[3] Hobbs, Phil. Mag. **10,** 617 (1905).

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

[5] Lilienfeld, Akad. d. Wiss. Leipzig, Ber. (Math. Phys. Kl) **62,** 31 (1920); Verh. d. Deutsch Phys. Ges. P. **11** (1921); Phys. Zeits. **20,** 280 (1919); Phys. Zeits. **23,** 506 (1922).

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

cal discussion of Schottky,[7] all indicate that electrons may be pulled out of metals by intense electrical fields. In particular the experiments of Hobbs, which were suggested by and carried out under the direction of one of the present authors, made possible the computations of the field strengths at which this effect begins to appear. Many years ago the first of us made these computations and then endeavored to check the values obtained by new experiments made with spherical electrodes about 1 mm apart in the highest obtainable vacuum. After continuing this investigation with many modifications intermittently for a considerable number of years it became evident that in a vacuum so high that the gas plays no further part in the discharge, the potential gradient at the metal surface necessary to obtain a discharge is exceedingly variable even for the same metal surface. The most recent of these results were published very briefly in 1920.[6] It was found that with clean untreated surfaces—two crossed tungsten wires, size No. 18, placed a small fraction of a millimeter apart—a first leak, as measured on a tilted electroscope, was obtained at a gradient of from 100,000 to 500,000 volts per centimeter. When heated to red heat and then cooled, these same surfaces gave a first leak at from 400,000 to 700,000 volts per centimeter. After heating to 2700°K the first leak was pushed up to 4,300,000 volts per centimeter and the first spark up to six million volts per centimeter. The present investigation is a continuation of this attempt to see just how far surface conditions control the field strength needed to pull electrons out of cold metals, and how "field-currents" depend upon field-strength, temperature, etc.

II. Apparatus and Method

Since we wished to make the distance between the electrodes of the order of a centimeter it became necessary to design the apparatus in a manner such that the field intensity at the surface to be investigated would be very large *because of the small radius of curvature of the surface* and such advance as we have here made has been due primarily to this condition. Accordingly a tungsten wire of .00123 cm diameter was placed at the axis of a copper cylinder of 1.625 cm diameter. From these dimensions the field strength F at the surface of the wire becomes

$$F = 228\ \phi$$

where ϕ is the difference in potential between the electrodes.

The tungsten wire W and the copper cylinder C were placed in a Pyrex glass tube as shown in Fig. 1. The wire is kept taut by a four-gram iron weight I, and is adjusted so as to be in the axis of the cylinder.

[7] Schottky, Zeits. f. Physik **14**, 80 (1923).

Two leads are connected to either end of the fine wire and then brought through a seal in the upper part of the tube. It is thus possible to send a current through the tungsten wire and thereby to heat it to any desired temperature. When the wire is heated to temperatures over 1100°K the iron weight is lifted by means of an electromagnet, *E*. With this arrangement one may keep the wire taut at low temperatures and yet be insured against its breakage at high temperatures.

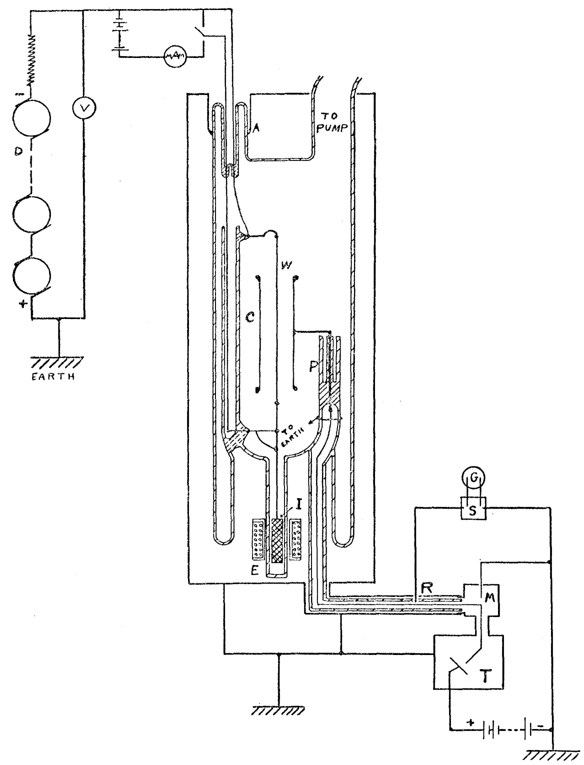

Fig. 1. Diagram of apparatus and electrical connections.

The cylinder is supported by a large tungsten wire that is sealed into the post *P*. This post has a glass sleeve to protect it from becoming coated with a deposit of copper when the cylinder is heated to bright redness in the process of denuding it of gases, otherwise the post might lose its insulating properties. An earthed guard ring is placed around the post *P* so that in case a charge should leak over the inside of the glass, none of it would reach the cylinder. The large tungsten wire passes through the seal in the post to the outside of the tube where it is joined to a copper wire leading to the tilted electroscope. A small glass tube is sealed to the main tube in such a manner as to enclose this conductor which is then electrically shielded by covering the glass with earthed tin-foil.

An electric heater surrounds the main glass tube. The metal cylinder on which the heating coils are wound is grounded and thus the heater serves as an electric shield for the tube. A grounded guard ring is placed at A to keep the outside of the tube from becoming charged when a high potential is applied.

Direct current generators are used as the source of high potential, the maximum voltage available being 12000 volts. In series with the generators is placed a resistance of a million ohms to protect the apparatus should a short circuit be established between the wire and the cylinder. A Max Kohl electrostatic voltmeter V, calibrated in place, is used to measure the potential applied between the wire and the cylinder. A tilted electroscope T and a galvanometer G provided with a variable shunt are used to measure the "field-current" between the wire and the cylinder. The wire to the galvanometer is disconnected at R when the tilted electroscope is being used.

After properly baking the tube and charcoal trap during exhaust, a pressure of less than 10^{-6} mm of mercury was obtained. The tube would stand over night with liquid air on charcoal and mercury vapor traps, and then show no measurable pressure on the McLeod gauge (reading to less than 10^{-5} mm), and when the pumps were running, as was always the case during observations, the pressure was certainly far below 10^{-6} though no attempt was made in these particular experiments to measure it accurately. However, with the use of high speed mercury pumps, wide openings, charcoal in liquid-air, and precautions for denuding, the vacua here used were presumably as high as can now be produced.

At the proper time in the investigation the cylinder was heated to cherry red for from eight to twelve minutes by electronic bombardment. The bombarding potential was 2,000 volts and the bombarding current 100 milliamperes. The filament used as the source of thermions is stretched in a series of zigzags around and within half a centimeter of the cylinder. This part of the apparatus is not shown in the figure.

If the wire is to be heated simultaneously with the application to it of a potential, the apparatus used to furnish and measure the heating current is placed on an insulated stand. Using data published by Langmuir[8] the temperature of the wire is obtained from the value of the current in the wire and its diameter.

[8] Langmuir, Phys. Rev. **7**, 302 (1916).

Observations were taken on three specimens of thoriated tungsten wire. These pieces were from the same spool and, as explained above, had a diameter of .00123 cm. When a new wire was introduced the tube was opened up, the wire supplied, and the tube sealed up again.

III. Results

(a) *The rapid rise of "field-current" with increasing potential gradient and the reversibility of the process.* The wires will be numbered I, II, III, the numbers indicating the order in which they were investigated. Fig. 2 presents the data obtained for wire I which had received no heat treatment other than that involved in baking out the tube, but which had been "conditioned," as explained below, by a .42 milliampere "field-current" (the current between the wire and the cylinder due to

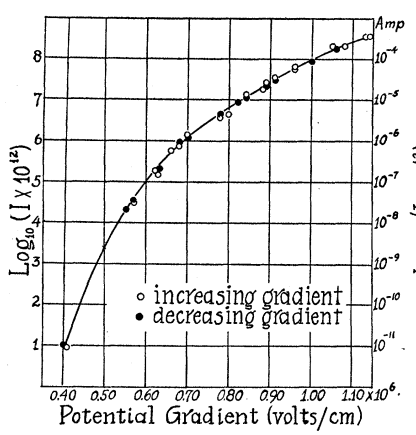

Fig. 2

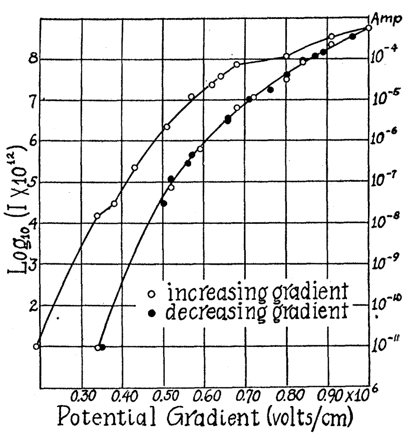

Fig. 3

Fig. 2. Variation of the logarithm of the "field-current" with potential gradient, for wire I, "conditioned" by a .42 m.a. "field-current."

Fig. 3. Variation of the logarithm of the "field-current" with potential gradient, for wire II, during and after "conditioning."

the pulling of electrons from the tungsten wire by the field alone). The figure clearly shows that *for a clean "field-current-conditioned" tungsten surface, but not heat-treated, the "field-current" increases more than ten-million-fold with a threefold increase of potential gradient,* i.e. *a gradient varying between* $.40\times10^6$ *and* 1.13×10^6 *Volt cm. These data further show that for "field-currents" lower than the current which conditioned the surface the process is quite accurately reversible.*

(b) *Conditioning the surface by means of "field-current."* "Field-currents" drawn from the surface for the first time, or for the first time after some sort of heat treatment, generally produce a permanent effect upon the surface, a sort of fatiguing effect that makes it more difficult to pull out electrons thereafter. This is shown in Fig. 3 which presents, in the upper curve, the first observations taken on wire II. After pushing the current up to the maximum shown, the currents obtained with diminishing applied potential are all below the corresponding value on the first rising-potential curve. However, the curve then becomes nearly reversibly reproducible until the current is pushed up above its former maximum value, an operation that again lowers the "field-current" for a given gradient. When the emitting surface has once been "conditioned" by drawing from it a large field current, and is not then subjected to further conditioning by current or by heat, it seems

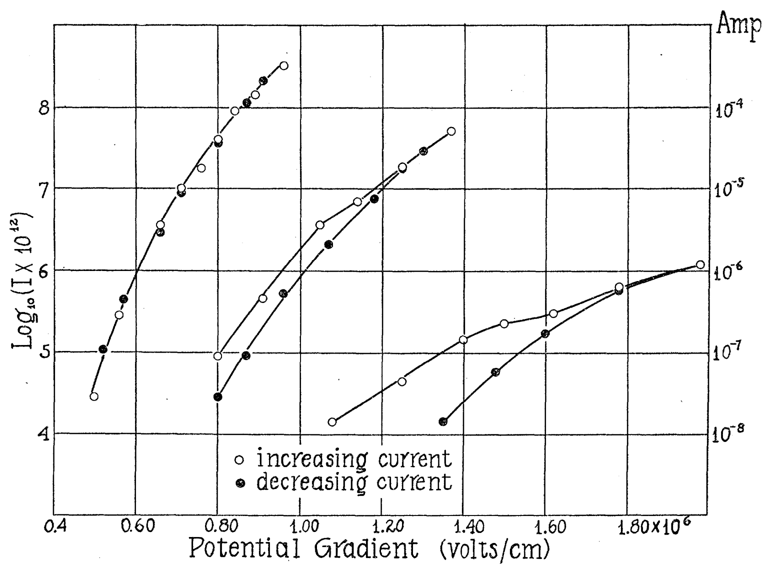

Fig. 4. The curves from left to right represent the data obtained on "current-conditioned" wires which have been heated to 700°K, 1300°K and 2700°K respectively.

to remain fairly constant and the current to become nearly reversibly reproducible (Fig. 3). But intense heat treatment modifies this condition as explained in connection with the data represented in Fig. 4.

Further, field-currents may be drawn for hours at a time without changing appreciably the "critical" potential gradient[9] except in the case of surfaces which have undergone intense heat treatment, and in this case the change due to the heat treatment does not appear to be permanent.

[9] In what follows, "critical" gradient is the potential gradient needed to produce a "field current" of 9.7 10^{-12} amp.

In one case a gradient of 1.7×10^6 v/cm applied to a surface which had been subjected to extreme heat treatment produced what we shall speak of as a rupture of the surface, for the "field-currents" increased slowly until this gradient was reached and then suddenly jumped up a thousandfold. Two definite spots on the anode opposite the regions of rupture appeared for the first time and these regions gave off nearly the whole of the current, for only two spots could be seen on the outer surrounding cylinder. Not only was the current for a given gradient increased, but the "critical" gradient was changed from 0.74×10^6 to 0.48×10^6 v/cm. This observation was made on wire III. No similar effect was observed on the other wires.

(c) *Conditioning the surface by heat treatment.* The effect produced by heating the wire is so dependent upon the way the impurities on the surface respond to different temperatures, that we shall divide the results of heat treatment into a number of parts, using the temperature range as the criterion of division.

TABLE I

Wire	"Critical" gradient[9] before baking	after baking	Maximum temp. of baking
I	0.48×10^6v/cm	0.37×10^6 v/cm	360°C
I	0.40	0.38	420°C
II	0.40	0.34	420°C

Long baking of the whole tube at 400°C reduced very slightly the critical potential gradient of a "field-current-conditioned" wire, this in spite of the fact that no change ever took place when the tube stood over night, or for a number of days, provided the vacuum was maintained during this time. The small, but apparently real, change with baking is shown by the data of Table I.

TABLE II

Conditioning "field-current"	"Critical" gradient after "field-current" conditioning (before heating)	(after heating)	Temperature	Total time of heating after conditioning
0.70 m. a.	0.41	0.32	900°K	10 min.
0.24	0.41	0.38	900	15
0.24	0.41	0.41	900	10
0.24	0.41	0.24	1100	5
1.05	0.40	0.27	1100	15
		0.24	1100	30
		0.22	1100	45
		0.21	1100	60
		0.22	1100	90

Heating wire II at 900° to 1100°K largely reduced the "critical" gradient of a "current-conditioned" surface. The "critical" gradient was re-established, however, by the "current-conditioning" process; in fact the phenomenon is roughly reversible, but becomes less pronounced with continued treatment as may be seen from a consideration of the data of Table II.

The effect of raising the tungsten wire to a very high temperature is to increase markedly the critical gradient. This is shown in Table III. It checks a result previously found by Millikan and Shackelford (l. c.). This increase in critical gradient with intense heat treatment is not permanent but disappears on long standing as though the surface underwent slow chemical change.

TABLE III

Temperature	Total time of heating at the particular temp.	Resulting "critical" gradient
1100°K	10 min.	0.39×10^6v/cm
1300	10	0.39
1500	10	0.31
	25	0.26
	40	0.29
1700[10]	20	0.27
1900	10	0.57
	25	0.46
	40	0.34[11]
	55	0.61
1800	15	0.46
	30	0.42
	45	0.68
2300	10	0.74

(d) *Slope of "field-current"-gradient curve a function of "critical" gradient.* The rate of increase of the "field-current" with the potential gradient is large when the "critical" potential gradient is small and vice versa. This is clearly shown in Fig. 4. It is also an observation which had been made previously by the first of the authors. Further, the higher the "critical" gradient, which corresponds to a higher temperature in the heat treatment, the less the constancy and the less the reversibility of the field-current-gradient curves. This is shown clearly in Fig. 4.

(e) *The "field-currents" in general have their origin in a few minute surface spots.* For small currents, less than 10^{-6} amperes, and for corresponding potentials less than 4000 volts, the tube remains perfectly black as viewed in a darkened room. (Currents lower than these may produce a luminous effect if the potential is sufficiently high.) For larger currents luminous spots begin to appear on the inner surface of

[10] This temperature and those below it may be too high by 100° to 200°.

[11] This decrease in critical gradient at 1900°K is probably due to thorium which first comes to the surface at this temperature and on continued heating evaporates from it (see Langmuir, Phys. Rev. *22*, 357 (1923)).

the cylinder and fluorescent spots to appear on the glass wall directly out from the top of the cylinder. The spots must be due to streams of electrons shot out from active spots on the surface of the wire.

The patches of light on the cylinder are reddish-grey in color and as viewed through a direct-vision prism seem to have a continuous spectrum. However, this point should be tested more carefully in an apparatus designed for this purpose.

As the "field-current" increases the spots become brighter and new spots may appear. Some of the spots are fixed in position and for a given current, constant in luminosity; others are slightly changeable in position, and before a steady current state is reached, rather changeable in intensity, and even when the current appears steady there is some variation in these points.

TABLE IV

Wire	"Critical" gradient 300°K	900°K
I	0.415×10^6v/cm.	0.408×10^6v/cm.
	0.409	0.410
	0.417	0.408
	0.417	0.410
	0.413	0.410
		0.413
I	0.670	0.672
	0.672	0.670
	0.670	0.655
	0.655	
II	0.730	0.730
	0.741	0.736
	0.741	0.741
	0.741	

Sometimes in the "current-conditioning" process, very brilliant spots spring into existence. This is well illustrated by the action of wire II. An irregularity was noticed in the "field-current" and on looking into the tube a new spot was seen on the cylinder near its center. The spot was changeable in intensity but fixed in position. Its intensity slowly decreased and its luminosity became more steady. Thereafter, the current ceased to fluctuate. Another interesting case is that mentioned under (*b*) in connection with the study of wire III. The wire had been heat-conditioned and was giving off very small "field-currents" considering the magnitude of the potential applied. There were only slight traces of luminosity. The next small increase of potential produced the thousand-fold increase in current and two luminous spots had sprung into existence. They furnished practically all of the "field-current," which was rather unsteady. These spots were fixed in position, but very changeable in intensity. The luminosity slowly decreased with continuous operation and the current settled into a more or less steady state.

(f) *The "critical" gradients and the "field-currents" are completely independent of temperature between 300°K and 1000°K.* Only data for the temperature of 900°K will here be recorded, although the effect of lower temperatures was investigated. Wires I and II were studied for this effect; the different "critical" gradients for the same wire are due to the previous conditioning process. The results are recorded in Tables IV and V.

TABLE V

Wire	Potential difference (volts)	Potential gradient (volts/cm)	"Field current" (amp.) 900°K	300°K	900°K	300°K
II	1730	0.39×10^{6}	9.7×10^{-12}	9.7×10^{-12}	9.7×10^{-12}	9.7×10^{-12}
	2500	0.57	9.0×10^{-8}	9.0×10^{-8}	9.0×10^{-8}	9.0×10^{-8}
	3000	0.68	1.9×10^{-6}	1.8×10^{-6}	1.8×10^{-6}	1.8×10^{-6}
	3500	0.80	6.0×10^{-6}	6.0×10^{-6}	5.7×10^{-6}	5.7×10^{-6}
	4000	0.91	4.4×10^{-5}	3.9×10^{-5}	4.2×10^{-5}	4.1×10^{-5}
	4550	1.04	2.4×10^{-4}	2.3×10^{-4}	2.3×10^{-4}	2.3×10^{-4}
	4000	0.91	4.2×10^{-5}	4.2×10^{-5}	4.4×10^{-5}	4.4×10^{-5}
	3500	0.80	7.2×10^{-6}	7.1×10^{-6}	7.2×10^{-6}	7.2×10^{-6}
	3000	0.68	6.9×10^{-7}	6.3×10^{-7}	7.2×10^{-7}	6.9×10^{-7}
	2500	0.57	3.0×10^{-8}	3.0×10^{-8}	3.0×10^{-8}	3.0×10^{-8}
	1810	0.41	9.7×10^{-12}	9.7×10^{-12}	9.7×10^{-12}	9.7×10^{-12}
I	8450	1.92	9.0×10^{-7}	9.0×10^{-7}		

(g) *The "critical" gradients and "field-currents" with a tungsten wire at 1100°K.* (The wire is of a just-visible-red color.) The extent of the lowering of the "critical" gradient with this temperature depends upon the magnitude of the "critical" gradient at ordinary temperatures, *zero effect being observed for very low gradients and a considerable effect for higher gradients* (Table VI). The magnitudes of the "critical" gradients at ordinary temperature are, of course, the result of past treatment of the surface. Further, when the gradient is sufficiently high so that the field-currents at 1100°K are observably higher than those at 300°K, *the percentage of increase in current due to this 800° rise in temperature is quite as high for large currents (10^{-4} amperes) as for currents of one thousandth, or even one ten thousandth of this value, thus showing definitely that field currents and thermionic currents are not entirely independent phenomena,* (See §IV(f), below) *since otherwise their effects would be additive.* (See Table VII for the experimental data.)

IV. Interpretation of the Foregoing Results

(a) *Field currents due to "conduction" electrons.* The magnitude and the reversibility of the foregoing field-currents indicate that the electrons which are pulled out of a metal by a sufficiently intense field are the free or conduction electrons[12] of the metal, as Schottky[7] has pre-

Table VI

Wire	"Critical" gradient 300°K (volts/cm)	1100°K (volts/cm)
II	0.212×10^6	0.212×10^6
	0.212	0.212
	0.214	0.213
	0.216	0.214
	0.215	
	0.317	0.310
	0.317	0.310
	0.315	
	0.450	0.358
	0.456	0.360
	0.458	0.364
	0.800	0.560
	0.800	0.561
	0.792	0.560
	0.402	0.315
	0.402	0.319
	0.399	0.322
	0.400	0.335
	0.399	0.335
	0.399	

Table VII

Wire	Potential difference (volts)	Potential gradient (volts/cm)	"Field-current" (amp) 300°K	1100°K	300°K
I	2600	0.59×10^6	1.2×10^{-8}	1.5×10^{-8}	1.5×10^{-8}
	3050	0.70	1.2×10^{-7}	1.4×10^{-7}	1.2×10^{-7}
	3500	0.80	6.0×10^{-7}	7.5×10^{-7}	6.0×10^{-7}
	4000	0.91	4.5×10^{-6}	5.4×10^{-6}	4.4×10^{-6}
	4400	1.00	2.1×10^{-5}	2.4×10^{-5}	2.1×10^{-5}
	4750	1.08	5.4×10^{-5}	5.9×10^{-5}	5.4×10^{-5}
	5000	1.14	1.0×10^{-4}	1.1×10^{-4}	1.0×10^{-4}
	4800	1.09	6.3×10^{-5}	6.9×10^{-5}	6.0×10^{-5}
	4200	0.96	1.2×10^{-5}	1.5×10^{-5}	1.2×10^{-5}
	3750	0.85	2.1×10^{-6}	2.7×10^{-6}	2.1×10^{-6}
	3200	0.73	2.4×10^{-7}	3.6×10^{-7}	2.4×10^{-7}
	3000	0.68	9.0×10^{-8}	1.5×10^{-7}	1.0×10^{-7}

[12] Conduction electrons are here defined as those that are responsible for the Ohm's law effects. They are free merely in the sense that there is no assignable lower limit to the e.m.f. that is required to set them streaming through the conductor.

viously assumed. For first, such large and constant electronic flows, of indefinite duration, would exhaust any other conceivable supply; second, the forces that are here involved are of an altogether different order of magnitude from those necessary to detach any bound electrons of which we have any knowledge. Thus the radiating potential of an atom which holds its outer electrons as loosely as does even sodium, for example, is about 2 volts, and by the application of these 2 volts, the electron is lifted through a distance of about 2×10^{-8} cm, i.e. from the normal position to its first excited position in which the diameter of the atom is about three times its normal diameter.[13] The lower limit to the field-strength, then, which would be required to pull off the electron of sodium from its normal position should be about $2/2\times 10^{-8} = 100,000,000$ volts per cm. But these experiments show that field-currents begin to be obtained with the application of a field-strength (potential gradient) of less than 1/200 of this, or 500,000 volts per cm. No bound electron, then, of which we have any knowledge, i.e. no electrons which may be regarded as belonging to particular atoms, are held so loosely as to make it at all possible to consider them as the electrons which here escape. *We therefore regard our fields as reaching sufficiently into the metal to get hold of and pull out some of its conduction electrons.*

(b) *Effect of sub-microscopic irregularities.* The field-currents here studied consist of electrons which escape only from isolated points on the surface where the work function b has been enormously reduced by microscopic geometrical roughnesses, or chemical impurities, or both. The spotted character of the glow on the anticathode is sufficient proof that the discharge actually does come only from specially favored points on the cathode. Further, Schottky[7] has pointed out that it would require a field-strength of the order of 100,000,000 volts per cm merely to counteract (at a distance of 10^{-8} cm, where the electron may be assumed to start) the image-force due to an electron escaping *from a plane surface*; so that neither free nor bound electrons could possibly be pulled away from such a plane surface by the fields used in the foregoing experiments. We can, however, call upon geometrical roughnesses in the surface, of large dimensions in relation to molecular diameters, to reduce the required forces to the observed values. Chemical impurities may obviously assist somewhat in developing such weak points in the surface.

(c) *Conditioning effects of currents, presumably due to positive-ion bombardment.* The conditioning of the surface by means of strong field currents is presumably due to the battering down or rounding off by

[13] H. A. Stuart, Zeits. f. Physik **32,** 262 (1925).

positive-ion bombardment of the microscopic mountain peaks which act as the electron-emitting points of the surface.

The most sensitive means that we have of measuring extremely high vacua is the ionization manometer or Buckley gauge.[14] With this gauge electron currents of the order of milliamperes, such as are here obtained, produce enough positive ions to be easily measurable in the highest vacua that have ever been produced. The electron currents obtained in the present experiments come from a very few points and hence constitute extraordinarily dense electron streams, or pencils, following the direction of the lines of force at the surface. The positive ions formed in these pencils must in these very intense fields return along the same lines of force and bombard almost exclusively the points in the surface at which the electron pencils originate. This theory accounts very satisfactorily for the observed dimming of an anticathode spot with time, the sub-microscopic protuberance having been gradually beaten down into insensitiveness by this bombardment.

(d) *Conditioning effect of heat treatment due to geometrical and chemical changes in the surface.* The lowering of the critical gradient by general heat treatment (Tables I and II) is presumably due to the contamination of the surfaces by emitted gases, while the large increase in the critical gradient by the intense heat treatment of the emitting wire (Table III) is due to the rounding off of surface irregularities supplemented by the removal of surface impurities.

The rounding off of protuberances either by heat or by bombardment should produce all the effects shown in Fig. 4, namely, (1) increase of critical gradient with treatment since both kinds of treatment should reduce the protuberances; (2) decrease of rate of rise of field-currents with applied potential, since the contrast between the peak and its surroundings has been reduced by the treatment and the surface concentration of the field and also of the positive ion bombardment at the sensitive point has become less pronounced; (3) decrease of reversibility with increasing critical gradient, since heavy bombardment from a strong gradient ought to modify a surface more than would gentle bombardment from a weaker one. Indeed, with increasing critical gradient, i.e. increasing energy of bombardment, there is evidence that a definite rupture point of the surface is more and more nearly approached. When it is reached a disruptive discharge occurs by which the cathode may become pitted. This has been shown by point-to-plane discharges.

[14] O. E. Buckley, Nat. Acad. Sci., Proc. **2,** 683 (1916).

(c) *New proof that the energy of conduction electrons is independent of temperature.* The only preceding theoretical treatment[7] of field-currents assumes them to be composed of thermions escaping under their own energy of agitation through a boundary weakened by the external field. This conception is, we think, altogether irreconcilable with the foregoing data. Indeed, the entire independence upon temperature[15] of the field currents over a range of 700°C constitutes new and striking evidence that "equipartition" does not hold at all for the bulk of the conduction electrons in tungsten at ordinary temperatures. For when these conduction electrons escape as thermions, the law governing their escape is

$$i = AT^n \epsilon^{-b/T} \tag{1}$$

in which b is the work function of Richardson. The correctness of this thermionic equation is attested by a vast amount of experimental work. Now the effect of an externally applied field of such direction as to pull out electrons should be simply to weaken the effective value of the work function b and leave i in the foregoing equation varying as rapidly with T as it always does in thermionic experiments. *The fact, then, that in the present experiments i is not at all dependent upon T over a 700° interval means that the electrons pulled out by the fields here used are not thermions at all.* They might become such at high enough temperatures, but at temperatures up to 1000°K the electrons here pulled out can have no assistance at all from temperature in getting out, i.e., *they do not share in the thermal energy of agitation of the atoms.*

A little, but somewhat uncertain, evidence for this conclusion has been previously obtained by Davisson and Germer,[16] who could bring their two independent methods of measuring b into agreement within one per cent if the electrons within the metal had zero energy, while a discrepancy of 2.7 per cent appeared if the conduction electrons had the energy $3kT/2$. The evidence derived from the specific heats of metals is inconclusive, because the number of conduction electrons within a metal is entirely unknown. The present evidence, on the other hand, appears to be direct, accurate, and unambiguous for the non-participation of the great bulk of "field-current electrons" (conduction electrons) in thermal motion. There must of course be sufficient participation by a few conduction electrons to account for the Peltier and thermo-electric effects, but this is quite consistant with the quantum theory considerations here employed.

[15] Lilienfeld (l.c.) also reports such independence.
[16] Davisson and Germer, Phys. Rev. **20,** 300 (1922).

The energy of agitation of electrons within tungsten at ordinary temperatures must be altogether analogous to that of the atoms of solid elements at temperatures far below that at which Dulong and Pettits' law holds. The occasional atoms which escape from such a solid follow the Maxwell distribution law[17] and are in thermal equilibrium with the outside vapor, which obeys in all respects the gas laws, but the great mass of the atoms within the solid are devoid of energy of agitation and would be so found if a Maxwell demon could reach in and examine them as the field in the foregoing experiments reaches in and examines the state of agitation of the conduction electrons of the tungsten. *From the point of view here taken the conduction electrons are simply the lightest of the elements which, at ordinary temperatures, have taken on practically no kinetic energy, i.e., have zero specific heat, and which reach equipartition only at very high temperatures. Those of the conduction electrons which at any temperature have escaped from this zero-energy condition are the thermions.* If they carry the total atomic heat of the electrons and if this atomic heat follows the usual quantum law, then their number should increase, at low temperatures, with T^3. This would be consistent with Eq. (1).

(f) *Relations of field-currents and thermionic currents.* We have just seen that *at low temperatures* field currents bear no relation to thermionic currents and that their observed properties lead to the conclusion that the conduction electrons constituting them possess no agitational (temperature) energies at all. But as shown in Table VII, at 1100°K thermionic currents of measurable magnitude (10^{-12} amp.) begin to appear from tungsten and consequently the thermionic equation begins to show evidences of having a role to play in the character of the emission. Thus with increasing potential gradient, the value of the effective work function b is continually reduced and hence the value of the thermionic part of the current (the increase at 1100° over that at 300°) continually rises as is beautifully shown in Table VII so that it makes as large a percentage of the total current when the latter is 10^{-4} amperes (potential difference 5000 volts) as when it is 10^{-8} amperes (potential difference 2600 volts).

Quite similarly, as shown in Table VI, strong fields begin at this temperature to bring into evidence the thermionic part of the current when weak fields are unable to do so. In other words, when the temperature is reached at which the number of thermions escaping without external field is at all comparable with the number constituting the

[17] See Germer's recent proof that the Maxwell distribution law holds accurately for thermions escaping into a high vacuum, Phys. Rev. **25**, 795 (1925).

field current at what we have called the critical potential gradient, the decrease in b due to increasing field pushes up the number of emitted thermions (the electrons coming out in accordance with Eq. (1)) slightly faster than the increase in field pulls out field-electrons. Another way of saying this is that field currents are a less rapidly rising function of the field than are thermionic currents (those following Eq. (1) with b regarded as a function of the applied field F.)

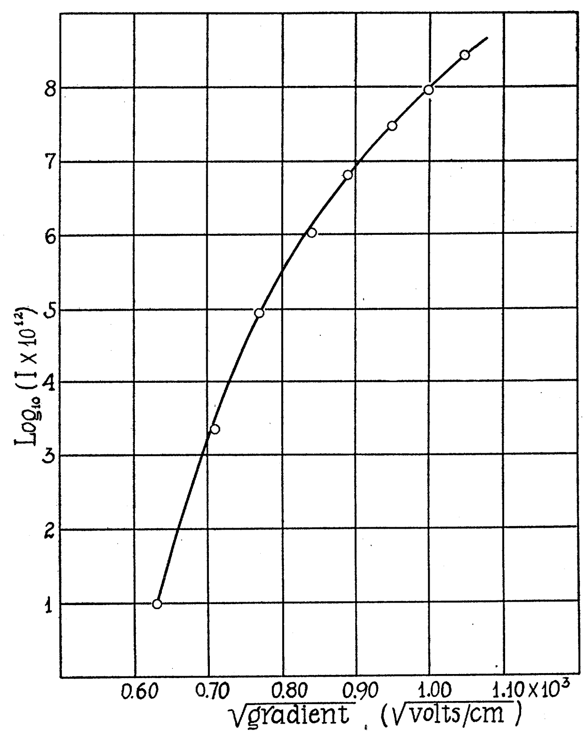

Fig. 5. Variation of the logarithm of the field current with the square root of the potential gradient.

A check on this conclusion may be obtained as follows: If the field currents were made up wholly of electrons, following Eq. (1) we could compute the relation between i and F if we knew how the effective work function b is diminished with increasing F. For sufficiently small values of F, where it is just beginning to influence b appreciably, it is possible to compute what sort of function of F the effective value of the work function is. For at a sufficient distance x_1 from the surface of the wire (a distance large compared to the surface irregularities) it is the image-force alone which must be overcome to cause the electron to leave the surface. The value of this image force per unit charge is $e/4x_1^2$. Every electron must escape which reaches the distance x_1 at which $e/4x_1^2=F$, i.e., at which $x_1=\sqrt{e/4F}$. Now the total work necessary to bring an electron out to x_1 is the work b_0 necessary to bring it up to the point x_0 at which the image law begins to be valid plus the integral $\int_{x_0}^{x_1}(e/4x^2-F)edx$. That is, the work function is

$$b_0+\int_{x_0}^{\sqrt{e/4F}}(e/4x^2-F)edx=b_0+e^2/4x_0-\sqrt{e^3F}+eFx_0$$

Since x_0 is very small (10^{-8} cm) the last term may be dropped while the first term is the total work necessary to bring the electron out *when there is no field*. Hence $b-\sqrt{e^3F}$ is the work function in the presence of an external field F and the thermionic equation becomes $i=AT^n\epsilon^{-(b-\sqrt{e^3F})/T}$. This equation shows that when T is constant and F alone varies $\log i\propto\sqrt{F}$. This equation should hold so long as all the escaping electrons are brought up to the point x_1 *by their own energy of agitation*. In other words, it should govern the increase in ordinary thermionic emission due to a relatively weak field F. Schottky[18] states that he has tested it for this case and found that the plotting of *log i* against $\sqrt{F}$ yields a straight line.

When, however, we plot for our cold wires log i against $\sqrt{F}$ *using the data given in Figs. 2, 3, or 4 we do not obtain a straight line but instead a curve continually concave toward the* $\sqrt{F}$ *axis* (see Fig. 5). *This means that our field currents do not rise as rapidly with increasing F as is demanded by the thermionic equation.* This is precisely the conclusion we drew from the data in Table VI.

All of our observed phenomena have now been rendered intelligible with the aid of the conceptions which we have herein used.

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California Institute of Technology,
October 25, 1925.

[18] Schottky, Jahrb. d. Radioakt. **12,** 203 (1915).