An Investigation of Irregularities in Thermionic Emission from Tungsten

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A tube employing a moving electrode is used to investigate variations in emission density over the length of a straight tungsten filament. After a critical temperature range is exceeded positive ion emission is shown to be limited to narrow regions near the lead wire connections. Electron emission, even after the filament is carefully aged, is not uniform from point to point, but occurs in a stable though irregular pattern. The irregularity is attributed to differences in work function or to differences in actual area covered by the slit or to a combination of both.

INTRODUCTION

IN a recent paper on emission patterns of cylindrical filaments, R. P. Johnson and W. Shockley[1] reported results obtained photographically from a tube employing a fluorescent screen and circumferential magnification. Photographic recording has also been used by other workers[2, 3] employing flat emitting surfaces and electron microscopes. Pinhole cameras have also found limited application.[4, 5] Quantitative measurements and systematic studies of both electron and positive ion emission from the same filament have not been reported in the literature, however, and the present paper will describe an experimental method developed for this purpose and used in a study of irregularities in the emission of electrons and impurities from tungsten.

EXPERIMENTAL TUBE

A slit arrangement was used, by which emission from selected small areas of a cylindrical filament could be measured. Values of the emission density computed from these measurements, when plotted against position along the filament length, showed longitudinal distribution of emission density. Data on either electrons or positive ions could be obtained by applying proper plate potentials. The principal features of the tube construction are covered in Fig. 1. Both the stationary and the sliding plates were made of seamless nickel tubing. The stationary plate had the diametral dimensions, 0.500-inch inside diameter and 0.520-inch outside diameter, maintained by the manufacturer. To form the sliding plate some of the same stock was forced over an enlarging mandrel to increase the inside diameter to 0.530 inch and was then annealed in a hydrogen furnace. The window was cut in the stationary plate by means of a sharp scribing point. The 0.008-inch slit in the sliding plate was made with a milling cutter.

The filament was accurately centered at the axis of the plate by means of special beryllia insulators supported in nickel spiders. Two quartz beads of the type used in FP-54 pliotron tubes supported the collector on the sliding plate and two others supported a trolley wire in back of the stationary plate. Special precautions were taken to have reliable contact between the collector and the trolley wire. Two connections were made, one a coil of 0.00175-inch nickel wire, the other a spring contact of 0.010-inch nickel wire. Throughout the duration of the tests both contacts remained intact.

Four 0.007-inch thoriated filaments were mounted in a side tube for better purposes and an ionization gauge was permanently connected to the tube to provide a check of vacuum conditions throughout the test.

A scale and vernier arrangement, by which the position of the slit relative to the filament was determined, could be read to 1/20 mm of any desired position. The scale was engraved on the stationary plate and the vernier on the sliding plate.

All parts were carefully designed to facilitate bakeout in the induction furnace. Regardless of how carefully the plates were polished before assembly to permit easy sliding, however, it was found that bakeout roughened the surfaces so

[1] Johnson and Shockley, Phys. Rev. **49**, 436 (1936).
[2] Bruche and Scherzer, *Geometrische Elektronen Optik* (1934).
[3] W. H. Brattain, cf. Becker, Rev. Mod. Phys. **7**, 118 (1935).
[4] H. Seemann, Zeits. f. Physik **79**, 742 (1932).
[5] A. J. Dempster, Phys. Rev. **46**, 165 (1934).

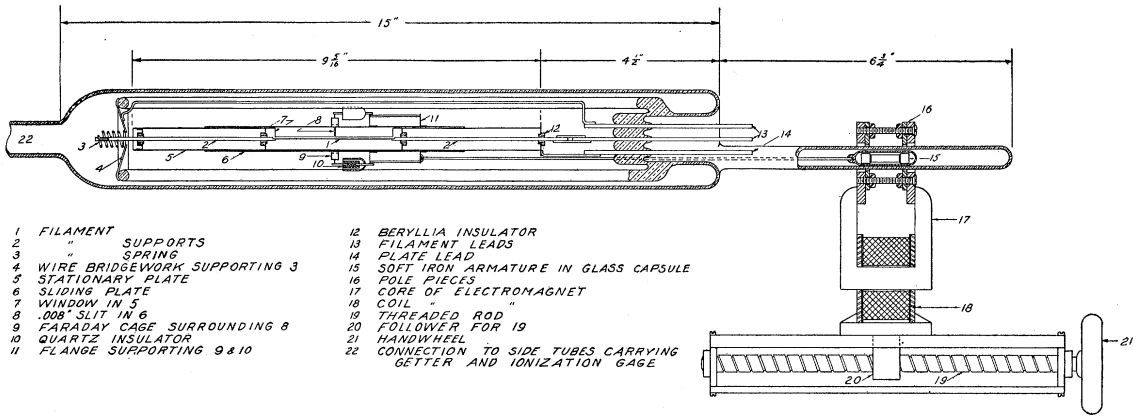

FIG. 1. Layout of the experimental tube and magnetic control. The flexible lead from 9 is not shown, but extends through a seal on the back of the tube.

badly that the full force of the magnetic control was necessary. This amounted to a pull of about a pound.

Throughout the test, the pressure in the tube as indicated continuously by the ionization gauge, was maintained at 2×10^{-7} millimeters of mercury or less. Any gas evolved was taken up by burning the thoriated filaments.

THE MEASURING CIRCUIT

The major features of the tube circuit are shown in Fig. 2. The filament current was accurately controlled and measured with a Leeds and Northrup Type K potentiometer, and could be reversed by means of the switch shown. The voltmeter was used to make occasional checks on the IR drop through the filament to verify the dimensional constancy of the wire. Appreciable evaporation of tungsten would, of course, increase the voltmeter reading for a given value of the filament current. The sliding and stationary plates of the experimental tube were at the same potential by virtue of their metallic contact. The potential of both relative to the filament was maintained by "B" batteries whose connections could be reversed to accelerate either electrons or positive ions as required. For all measurements reported in this paper the plate to filament potential was 200 volts. Currents to the collector were distributed over a range from 10^{-4} to 10^{-16} ampere necessitating an extremely flexible measuring circuit. For the small currents a DuBridge-Brown pliotron circuit[6] was used to measure the drop across one of three high resistors of different values. For the larger currents a shunted galvanometer was used. Actually the same galvanometer served for the pliotron circuit and for direct measurements, a reversing switch being provided in addition to permit the change from positive ion to electron measurement.

POSITIVE ION RESULTS

Temperature gradient along the length of filaments is the most easily recognizable cause of longitudinal differences in emission density. At low filament temperatures the lead connections are near room temperature and a maximum occurs near the half-way point on the length of the filament. As the filament current is increased the maximum value of the temperature increases and gradually stretches out into a plateau region of more or less constant value. The maximum may be determined to a sufficient degree of accuracy for most requirements from

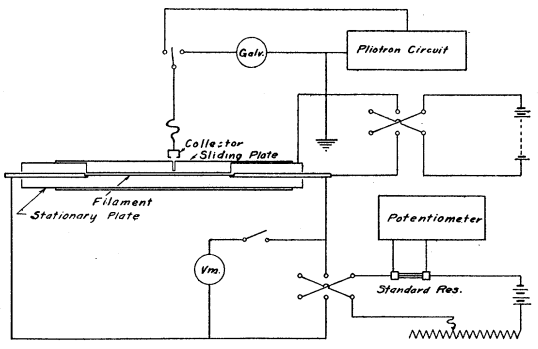

FIG. 2. Wiring diagram.

[6] DuBridge and Brown, Rev. Sci. Inst. **4**, 532 (1933).

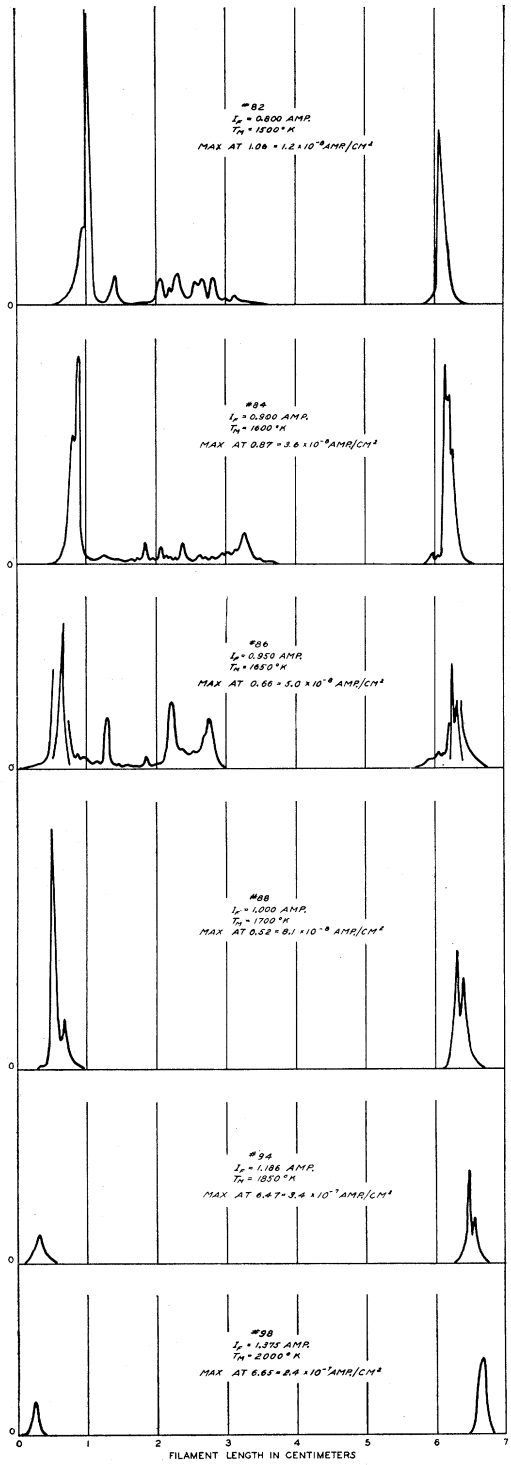

FIG. 3. Longitudinal distribution of positive ion emission at various stages of the aging process. The maxima of curve 86 are plotted to 1/10 the scale of other points.

the data of Jones and Langmuir.[7] At the ends, thermal conduction by the lead wires causes a temperature gradient from the plateau value to the temperature of the leads as described by Langmuir, McLane and Blodgett.[8] Neither the maximum temperature nor the end losses can be precisely calculated, however, since emission currents are frequently appreciable in comparison with the heating current, and because the temperature of the lead wire connection is normally indeterminate experimentally.

For regular thermal emission of electrons or of characteristic ions[9] the emission density is an increasing function of the temperature. The emission of ions of impurities, on the other hand, is not an increasing function over the entire temperature range, but increases to a maximum and then decreases as the temperature is raised further.

The phenomenon behaves as though a critical temperature exists at which ion emission is a maximum. Thus as the temperature of an unaged filament is increased, emission of ions of impurities will increase until the critical temperature is reached and will then decrease with further increases in temperature. Regardless of the influence of other factors it is likely that the principal reason for the critical temperature is the cleaning of the wire in the hotter regions. Above the critical temperature the surface coating is very thin or nonexistent, whereas it may give rise to very strong currents at or below the critical temperature. This lends considerable weight to the assumption that tungsten can be adequately cleaned for experiments on electron emission, a conclusion which will be substantiated by electron data to be given later.

Experimental results for a 0.0048-inch Fansteel tungsten wire are shown in Fig. 3 for various temperatures. The filament had not been burned previously above 1400°K, hence the distributions represent successive stages in the aging of a raw filament.

Curve 82 represents the distribution of ion emission corresponding to a temperature maximum of 1500°K and a temperature gradient beginning near the center and extending to a

[7] Jones and Langmuir, General Electric Reprint, 1927.
[8] Langmuir, McLane and Blodgett, Phys. Rev. **36**, 478 (1930).
[9] L. P. Smith, Phys. Rev. **35**, 390 (1930).

minimum at the lead connections. The regions of greatest emission density show irregularities such as that at 0.97 cm which may be evidence either of different chemical components in the surface coating or of irregular distribution of the surface film. A surface coating of more durable nature is indicated by the emission from 1.2 to 3.6 cm. No emission was observed between 3.6 and 5.8 cm with a sensitivity that would have detected emission densities of 10^{-11} amp./cm^2.

The sequence of curves following 82 represents emission distributions at successively higher temperatures. It can be seen that as the temperature is increased and the region of relatively uniform temperature widens out into a more extensive plateau, the increasing temperature near the lead wires causes the maxima to shift progressively toward the ends.

In addition to temperature dependence, two other factors are important in considering emission of positive ions from the cooler portions of filaments. The first of these is variation with time, and the second is the influence of the applied electric field.

Before beginning the set of observations shown in Fig. 4, to illustrate the change of ion emission with time, the filament was maintained at 1700°K for several hours with an electron accelerating voltage of +200 volts. The ion collector was set to receive ions from the "6.5 cm" region of the filament and the potential was reversed to −200 volts at the time $t=0$. It is therefore clear that the intensity of ion emission is subject to great changes with time, and in a negative field will decrease. From the rapidity of the initial decay it is seen that a curve such as 94 cannot be obtained until the decay has leveled off to relatively stable values, since a single traverse for ion distribution over the end regions involves about a hundred and fifty experimental points and takes about two hours time. Hence, the distribution curves do not represent maximum values, and do not represent instantaneous distributions. Thus, on curve 94 for example, the crest at 6.47 cm does not accurately correspond to the crest at 0.31 cm since the two were not obtained simultaneously. Furthermore, the shapes of the peaks are subject to some distortion for the same reason.

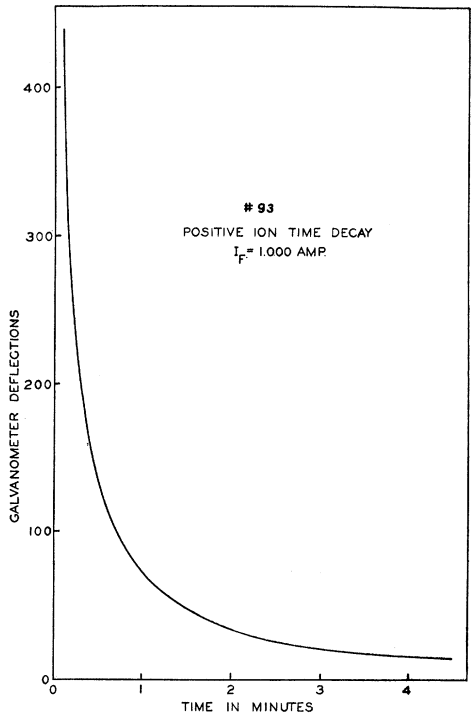

FIG. 4. Decay of positive ion emission with time.

The second factor is dependence upon field conditions, since experimental data indicate that the density of the surface contamination is influenced by the nature of the applied field. For example, the rapidity of the initial decay after the application of a negative field, as on curve 93, suggests that impurity had been collecting on the surface of the filament under the retarding positive field. Under a continuously negative field nothing but decay of the ion emission has ever been observed, while the decay phenomenon just described is characteristic of ion emission immediately after reversal of the field from retarding to accelerating. In some instances it is even possible that a relatively stable increase in the positive ion emission will result from a retarding field without changing other conditions. A comparison of curves 44 and 45, Fig. 5, will serve to illustrate this. Curve 44 was obtained after an extended period of decay. A retarding field was then applied for several hours. Characteristically rapid decay starting from values much greater than those of 44 occurred when the field was reversed. As soon as the decay had become quite gradual curve 45

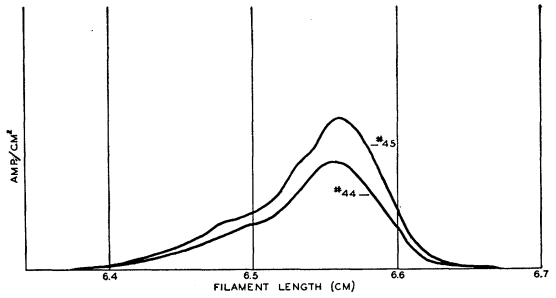

FIG. 5. Rebuilding of a surface coating of impurities in a negative applied field.

was obtained. Thus in spite of the completion of the early rapid stages of decay a sufficient change had taken place to give increased stable values of ion emission, and even though neutral atoms may evaporate from the surface at these temperatures, evaporation is not independent of applied electric fields.

ELECTRON RESULTS

On curve 82, Fig. 3, there is a component of positive ion emission near the central region of the filament which was durable at much higher temperatures than the surface coatings nearer the ends. Its durability was suggestive of an oxide coating. Curve 83, Fig. 6, taken at the same temperature shows that electron emission is measurable only where there is no emission of positive ions. Thus the surface coating in the region from 1.2 to 3.6 cm on curve 82 gave the filament a high electronic work function tending to confirm the previous suggestion in regard to its chemical nature.

At 1700°K emission of electrons takes place from regions of differing surface conditions as shown on curve 92. Areas of low work function resulting from a surface coating give rise to pronounced maxima near the ends. The central region is presumably considerably cleaner than the end regions, and has, therefore, a higher work function. The emission structure is extremely irregular as demonstrated by the numerous and pronounced irregularities in the curve. Variations of this kind could easily result from slight differences in the work function, and some of the variation could be due to changes in the actual area covered by the slit, a matter which will be discussed in greater detail later. Since the filament probably is not clean at this temperature it is reasonable to attribute the structure to patchlike distributions of the surface coating and consequent variations of the work function over the successive rings covered by the slit in making a traverse along the length of the filament.

At 2000°K an extensive portion of the filament is at very nearly constant temperature. Also, at this temperature, emissivity from the central region is high compared with the limited emission from the contaminated end regions. These two facts are sufficient to account for a considerable change in the distribution of emission from that plotted on curve 92. The structure at 2000°K, as shown on curve 99, is relatively flat with the exception of four prominences. In the end region between 0 and 1 cm a hump is superimposed upon a general background of apparent emission giving evidence again of low work function in the cooler regions. This peak is roughly three times as high as the background values and the reduction of its value to a third would result in its loss. Under these circumstances, therefore, evidence of this sort cannot be expected in every case. There is no corresponding peak, for example, at the opposite end of the same distribution curve.

Curve 100 shows further development of structure in the central region of the filament at 2300°K. The four maxima which appear on curve 99 have widened out into regions of high emission separated from each other by narrow valleys. It was suspected that the major features of curve 100 would prove to be characteristic of a clean tungsten wire, but an accident destroyed this filament and subsequent tests were made on a new sample of the same stock.

Fig. 7 shows four distributions of electron emission over the new filament under various conditions. For comparison the curves are plotted in close proximity in numeric sequence and for convenience the scales are different and the origins are shifted.

Curve 105 taken at 2150°K was believed to show the emergence of structure characteristic of the new filament. Details are entirely different from those of curve 100, proving beyond any doubt that the geometry of the tube did not determine the structure.

The same structure persisted at 2300°K and 2450°K as shown by curves 106 and 107, respectively. These later curves also show a previously undemonstrated factor, namely greater emission from one end than from the other as the result of a differential in the heating effect. At the higher temperature the electron current to the plate was 54 milliamperes, and the filament current was, therefore, 54 milliamperes greater at the negative end than at the positive. Thus emission currents in general give rise to a longitudinal temperature gradient independent of that due to end cooling by the leads.

The filament was next burned at 2900°K for six minutes to complete the aging process of the wire in accordance with the usual thermionic practice for tungsten. After reducing the temperature to 2450°K again, curve 108 was obtained. The total electron emission to the plate corresponding to curve 108 was 56 milliamperes compared with a total value of 54 milliamperes for curve 107.

After curve 108 was taken the filament was aged continuously for two hours above 2900°K, but no major changes in the filament structure occurred. A further slight increase in the total emission at 2450°K resulted, however, as the result of evaporation of tungsten from the surface.

Conclusion

The cause of irregularities in electron emission distributions is not easy to explain. One may make several postulates including (a) the influence of impurities, (b) dimensional inconsistencies in the wire, (c) differences in the value of the work function, (d) differences in the actual area covered by a slit, and (e) the related Schottky effect.

The occurrence of impurities, at least as a major consideration, may be eliminated as a consequence of the observed emissions. The shift of positive ion emission toward the end regions of the filament as shown in Fig. 3, was an indication that the central region of the filament would eventually be thoroughly cleaned. It was noted that each increase in the temperature produced a definite shift of the ion emission toward the lead connections, thus supporting the deduction that cleaning of the surface at higher temperatures can be expected.

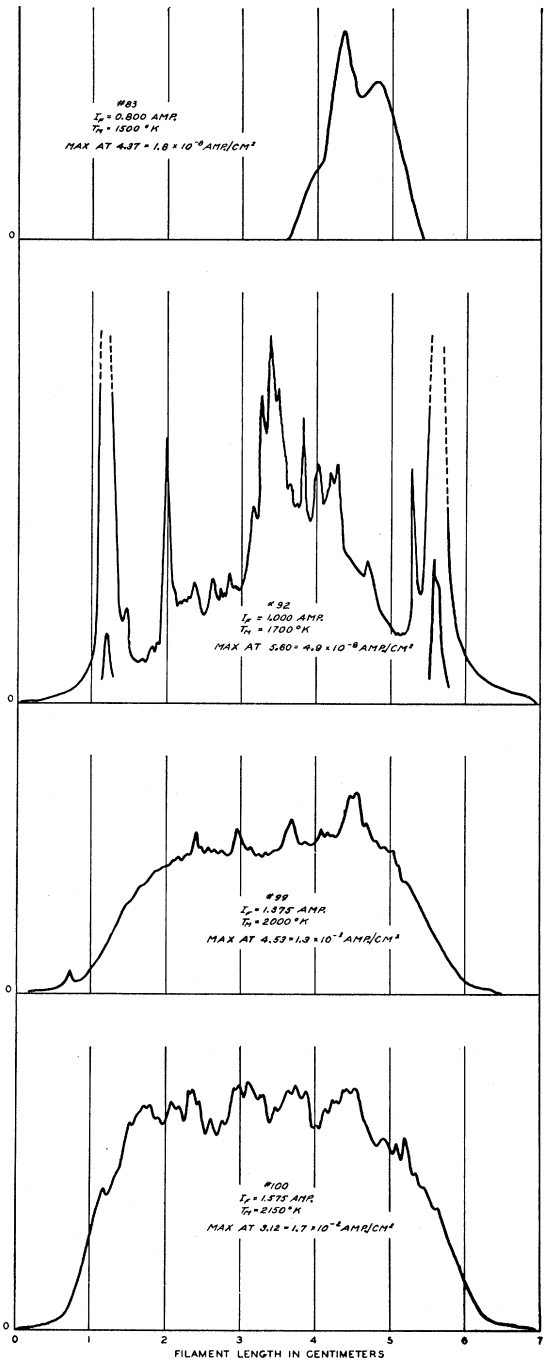

Fig. 6. Longitudinal distribution of electron emission at four stages of the aging process. The maxima of curve 92 are plotted to 1/10 the scale of other points.

Curve 92 indicates that surface impurities may give rise to abnormally high emission of electrons as shown by the peaks at the ends. The shift of

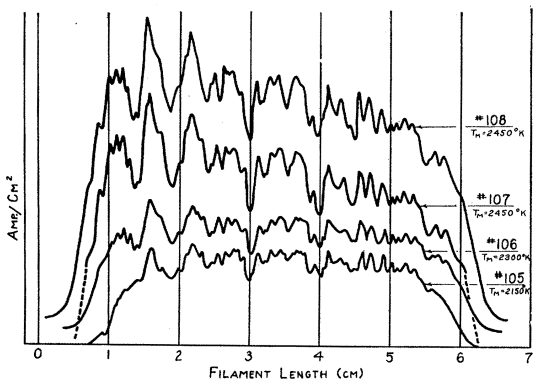

FIG. 7. Stability of characteristic electron emission distributions with various heat treatments. Curve 108 was obtained after flashing at 2900°K. Scales and origins were selected to facilitate comparison of the curves.

these maxima toward the ends with increasing temperature is evidenced by the peak occurring on curve 99 between 0 and 1 cm. The general conclusion from these data is that under usual conditions of thermionic experiments on tungsten, where data are taken from the central region of the filament only, impurities are not present in such a way as to effect the results. This conclusion is further supported by the curves of Fig. 7, which reveal the same structure after several heat treatments, yet changes would be expected if patches of impurity existed on the surface of the wire.

Dimensional irregularity can be eliminated as the cause of the observed structure by a series of simple calculations based upon curve 108. The peak at 1.6 cm on this curve is 44 percent higher than the minimum at 1.9 cm. By averaging out the structural irregularity, it is also noted that due to the 54 milliampere difference in the heating current at the two ends the general emission toward the negative end is roughly 45 percent greater than that near the positive end. The computations show that dimensional irregularities necessary to account for the emission pattern are greater than any variations actually present in the wire.

One objective of the test was to compare work function values from point to point on the filament in an effort to detect variation. Electrical difficulties with the circuit prevented a conclusive study of this quantity, although a value of 4.54 ev was indicated as the approximate value. In this connection it is important to consider the scale of the test. The apparent filament area covered by the slit and emitting electrons to the collector was 3.0×10^{-4} cm². If, as has been assumed, differences in work function are to be discovered between different crystalline faces, definite values will never be established by examination of such large areas. Etch facets on tungsten filaments are of a magnitude far inferior to 3×10^{-4} cm², and for that reason all data presented in this paper represent averages over serrated areas. It is probable in spite of this consideration, however, that with more precise technique applied to the same apparent area, a slight difference in the average work function would be detectable if one or another crystal face should predominate in making up the actual area of limited portions of the filament exterior. As indicated by Johnson and Shockley the difference might be pronounced in adjacent quarters of a filament circumference.

Differences in actual filament area covered by the slit, if independent of other factors which are possible contributors to the structure, could be used to account fully for irregularities of the observed magnitudes.[10] As shown by other investigators,[11] however, surface roughness results in the introduction of a necessary shape factor in applying the Schottky correction. Abnormally rough surfaces, at the points of which the electric fields are extremely high, make accurate revisions of the image force picture very difficult, and correction of the work function to zero field by application of the Schottky theory may be inadequate. The bearing this may have upon precise determination of work functions is obvious, even if it is granted that the difference in work function from face to face of certain crystals may be negligible.

In closing the author wishes to express appreciation of the friendly counsel of Professor Lloyd P. Smith, whose interest has contributed greatly to the progress of this work.

[10] L. Tonks, Phys. Rev. **38**, 1030 (1931).
[11] Compton and Langmuir, Rev. Mod. Phys. **2**, 149 (1930).