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SINGLE TUNGSTEN CRYSTALS

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RESEARCH LABORATORY OF ELECTRONICS
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M. K. Wilkinson

Abstract

A photometric method has been developed and used to measure field-emission electron currents quantitatively as a function of the crystallographic directions found in a single crystal emission point. One purpose of this study was to evaluate the exponent of the work-function needed to relate the field-emission equation to observed data. These experiments are in agreement with theory and indicate that $(3/2)$ is the most suitable value of this exponent. The method of analysis used here is independent of the need for high accuracy of the absolute field determination, but it does depend on a good knowledge of the relative field distribution over the surface of the crystal. In addition, it is assumed that the thermionically determined Richardson work-functions of Nichols are suitable for comparison.

To insure the required constancy of the electron emission for measurement, it was necessary to maintain a supervacuum. A method is given for the maintenance and measurement of such a vacuum. The vacuum attained was better than 10^{-12} mm.



CRYSTALLOGRAPHIC VARIATIONS OF FIELD EMISSION FROM SINGLE TUNGSTEN CRYSTALS

I. Introduction

Although the emission of electrons from cold metals by a strong electric field was discovered about thirty years ago, progress on this problem has been much slower than that for the allied field of thermionic emission. The explanation of this slow progress is probably the fact that the emissions were not reliable and seldom gave reproducible results. This fact limited their practical application, and consequently few experiments have been performed.

The most generally accepted theoretical explanation of field emission was first given by Fowler and Nordheim (1). This theory was modified by Nordheim (2), and subsequently, Sommerfeld and Bethe (3) gave a complete derivation. The expression obtained by them for the field-emission current was

$$J = 1.55 \times 10^{-6} \frac{F^2}{\phi} e^{-\left[6.86 \times 10^7 \phi^{3/2} v(y)\right]/F} \quad (1)$$

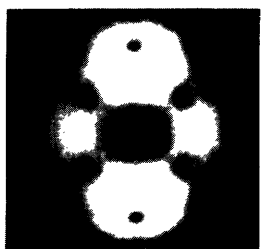
where

$$\begin{aligned} J &= \text{current density in amp/cm}^2 \\ \phi &= \text{work-function in electron volts} \\ F &= \text{electric field in volts/cm} \\ y &= 3.62 \times 10^{-4} F^{1/2}/\phi \\ v(y) &= \text{a slowly varying elliptic function of } y. \end{aligned}$$

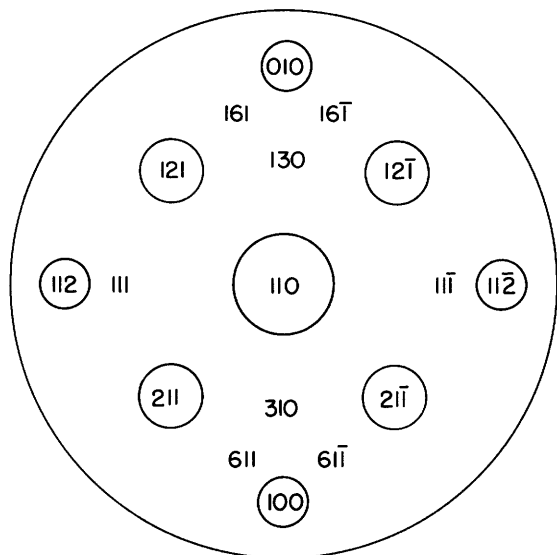
Since $v(y)$ varies such a small amount for the usual range in the surface field (F), data that fit this equation will fall on a nearly straight line when values of $\log(J/F^2)$ are plotted as a function of $(1/F)$. Houston (4) has shown that it is possible to prepare a table by which an observed average slope associated with a specific range in field can be corrected to account for the influence of the $v(y)$ function. After this small correction is made, an accurate value of the constant ϕ can be computed from the data if the field (F) is known accurately. The plot of $\log_{10}(J/F^2)$ against $(1/F)$ will be called the field-emission characteristic; and Eq. 1, the field-emission equation.

Previous experimental investigations of field emission may be classified into two general groups: (a) quantitative measurements to determine the applicability of the theoretical equation; (b) qualitative observations of contamination and migration with the field-emission projection tube. With regard to the former group, certain aspects of the theoretical equation have been proved, but there is disagreement on the type of dependence of the current density on the work-function. Results by Müller (5) disagree with the theory and indicate that the current density depends exponentially on the third power of the work-function, while later results by Haefer (6) require the $3/2$ power as predicted by the theory.

All quantitative measurements have been made on surfaces which do not possess a



(a)



(b)

Fig. 1

Field-emission pattern of a clean tungsten-point cathode; (a) projection-tube pattern; (b) crystal-surface diagram.

unique value of work-function. The experiments of Nichols (7) and Mendenhall and DeVoe (8) have assigned quantitative values to the work-functions for the various crystallographic directions. Since the quantitative measurements on field emission were taken simultaneously from a variety of crystallographic directions, they do not apply to a particular atomic surface structure, and the constants lack a definite physical interpretation. Experiments with the field-emission projection tube have led to a question concerning the type of pattern obtained. A photograph of a typical field-emission pattern for clean tungsten is shown in Fig. 1(a). Such a pattern portrays bright and dark spots which can be associated with emission along the various crystallographic directions, some of which are labelled in corresponding positions in Fig. 1(b). The puzzling feature concerning these patterns is the reason for the dark spots. Most observers have felt that the relative values of emission between bright and dark spots are much too large to be explained by the normal differences in the work-functions of the crystallographic directions. Many theories have been postulated, but none has given a satisfactory explanation.

The purpose of the present research was to study the relative field-emission currents along the main crystallographic directions of a single tungsten crystal. A projection tube was used so that the state of contamination of the cathode would always be known from the pattern which was obtained on the phosphor. The study was made by photometering the light output along the various crystallographic directions. These measurements gave relative field-emission currents, and slopes of the field-emission characteristics for the different crystallographic directions gave the relative magnitudes of the work-functions. These data led to an explanation for the existence of the dark spots on the field-emission pattern, and a comparison of the slopes of the field-emission characteristics with previously determined values of the work-functions gave more information regarding the validity of the theoretical equation.

II. Experimental Techniques

A. Design of the Experimental Tube. The first experimental tubes were constructed according to the conventional method of building field-emission projection tubes. In these tubes the phosphor is deposited directly on the glass envelope, and the high voltage is applied to a separate anode structure. The potential of the phosphor for a particular anode potential depends on the secondary-electron-emission properties of the phosphor and the efficiency of collection of the secondary electrons at the anode. Experimental results indicated that this type of tube is satisfactory for qualitative investigations of the field-emission pattern, provided the anode possesses sufficient surface area to make it an efficient collector of the secondary electrons emitted from the phosphor. However, such a tube is unsatisfactory for quantitative measurements. The actual potential of the phosphor was measured on one of the tubes and was found to be considerably less than that of the anode structure. Furthermore, the potential of the phosphor outside the field-emission pattern was different from that of the phosphor bombarded by the primary electrons. This distribution of potential made it impossible to make a satisfactory analysis of the photometric data which were obtained.

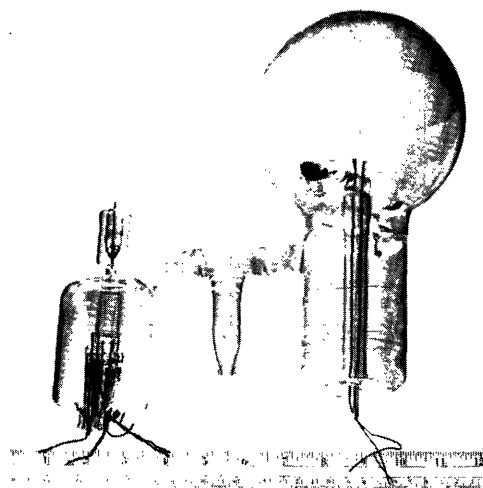


Fig. 2

Photograph of experimental tube with ion gauge.

The final experimental tube was constructed with a layer of "conducting glass" on the inside of the glass envelope, and the phosphor was deposited on top of this layer. Such a tube allowed the voltage to be applied directly to the spherical surface and thereby eliminated the difficulties experienced with tubes of the conventional type. The cathode was a sharp point etched electrolytically from tungsten wire in a solution of sodium hydroxide. This point was mounted on a tungsten hairpin so that it could be heated and outgassed. The phosphor (ZnS, silver-activated) was sprayed on the inside of the glass envelope from a solution containing a nitrocellulose binder. Phosphor was deposited only on the top one-third of the bulb to eliminate reflected light on the pattern from the bottom part of the tube. Furthermore, only a very thin

coating of phosphor was deposited to reduce to a minimum the diffusely scattered light from adjacent parts of the phosphor. A photograph of this tube connected to an ion gauge is shown in Fig. 2.

B. Vacuum Techniques. Early experiments with field-emission projection tubes have indicated the necessity of extreme vacuum conditions in order to obtain a pattern of clean tungsten which remains stable with time. Since the point cathode is maintained

at room temperature, any residual gas in the tube is quickly adsorbed on the point, and the pattern produced by the field-emission electrons changes. If the pressure is greater than 10^{-8} mm Hg, after the point is cleaned by a high temperature "flash," the pattern changes so rapidly with time that it is difficult to determine the pattern representative of clean tungsten.

The experimental tubes were pumped on a new vacuum system built specifically for this research to eliminate any possibility of vacuum problems due to any slightly contaminated parts of the vacuum system. The entire system was made of a Pyrex glass, and the glassware on the high-vacuum side was kept to a minimum. The tube to be evacuated was pumped by a cone-nozzle mercury-diffusion pump which was backed by a jet-mercury-diffusion pump, and the latter was backed by a mechanical pump. A liquid nitrogen trap was placed between the experimental tube and the cone-nozzle diffusion pump; ovens were arranged so that all the glassware on the high-vacuum side of the pumps could be baked.

The vacuum techniques used in this research were based on some earlier studies of field-emission projection tubes by Daniel (9) and Moore (10). Although these experimenters had no method of measuring a vacuum lower than the X-ray limit of the normal ion gauges (approximately 10^{-8} mm Hg), they obtained interesting and helpful results concerning the effect of certain procedures on the stability of a field-emission pattern. Data from extensive vacuum experiments by Nottingham (11) on ionization gauges were also extremely helpful. As shown in Fig. 2, an ion gauge was connected directly to the experimental tube so that the two could be sealed off the vacuum system simultaneously. Two types of ion gauges were used during the research: the conventional ion gauge with a flash filament, and the new type of ion gauge which has the elements inverted to reduce the X-ray limit of the gauge. The X-ray limit on the particular ion gauge that was used was approximately 5×10^{-11} mm; flash filament data allowed a rough approximation of lower pressures.

The tube and ion gauge were processed very thoroughly on the vacuum system by repeating a specific cycle of outgassing. This cycle was started after a pressure of the order of 10^{-9} mm had been reached by normal processing. It included the following steps:

1. The phosphor was bombarded by thermionic electrons for an hour to outgas the phosphor.
2. The metal parts of the tube and ion gauge were outgassed at high temperatures for thirty minutes. Those parts that could be heated by the passage of current were heated to approximately 2600°K; those parts that were heated by high-frequency induced currents or electron bombardment were heated to approximately 1900°K.
3. The glassware was baked at 425°C for about four hours. While the ovens were hot, the glass tubing around the diffusion pumps was torched thoroughly with a Bunsen flame. The trap oven was turned off, and liquid nitrogen was placed around the trap about thirty minutes before the tube oven was turned off.

4. The ion gauge was turned on and a record was kept of the pressure. There was always a slow decrease in pressure until a steady-state value was reached. As the pressure became lower, the time required to reach the steady-state condition became greater. Approximately twenty-four hours were required at the low pressures obtained just before sealoff.

5. When the steady-state pressure had been reached, the field-emission pattern was observed to determine its stability.

The procedure in the cycle outlined above was repeated until the ion gauge readings and the stability of the field-emission pattern indicated no change between two successive cycles. Approximately five cycles were normally required to fulfill this criterion, and the residual pressure was approximately 10^{-11} mm. Two preliminary sealoffs were made, during which an appreciable amount of gas was released from the sealoff constriction, and the cross-sectional area of the constriction was reduced to approximately one-half of its original size. After the second preliminary sealoff, another complete cycle of outgassing and baking was performed, and the tube was sealed off the vacuum system. The ion gauge was turned on, and its operation served to clean up some of the residual gas. The pressure decreased slowly and reached an equilibrium value of approximately 10^{-12} mm in about one week. At this final pressure in the sealed-off tube, the rate of contamination of the point cathode was very slow, and the field-emission pattern changed very slowly with time. The stability of the pattern is shown in the

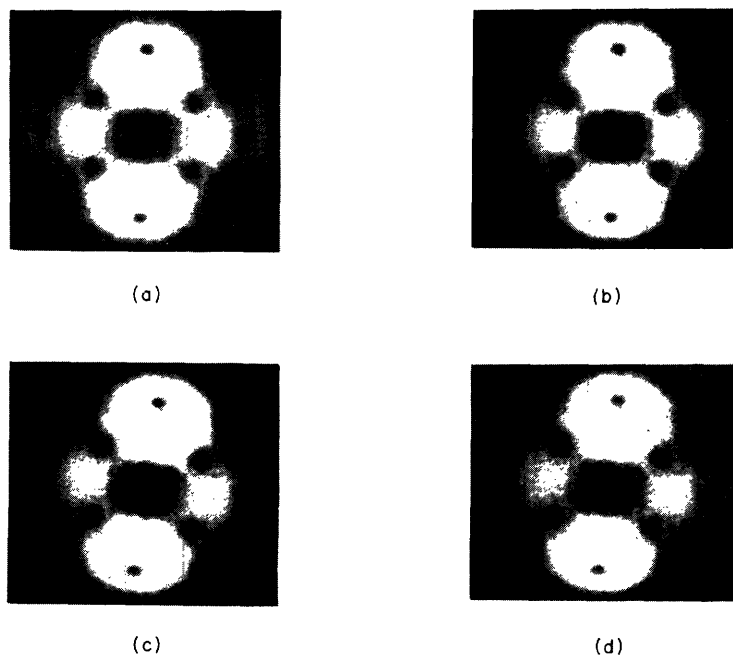


Fig. 3

Photographs showing rate of contamination of point cathode; (a) immediately after flash; (b) 12 hours after flash; (c) 24 hours after flash; (d) 48 hours after flash.

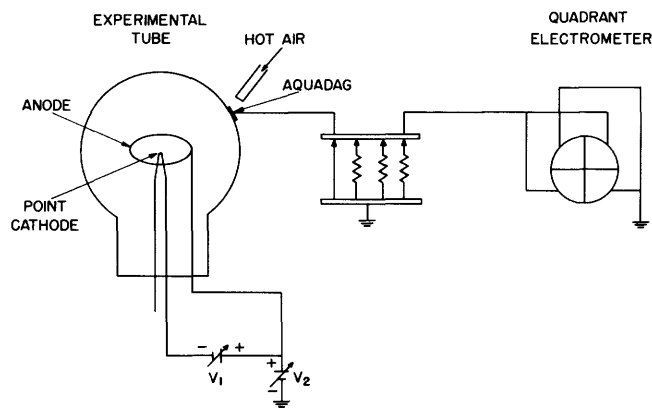


Fig. 4

Circuit diagram for measurement of phosphor potential in conventional field-emission projection tubes.

sequence of photographs in Fig. 3. This sequence was made with the electric field off, except when the photographs were taken. Another sequence of photographs was made with the electric field applied continuously. It was found that the contamination occurs slightly faster when the field is applied. In Fig. 3, the first signs of contamination are seen in the photograph taken twenty-four hours after cleaning the point cathode. In this photograph, the dark spots for the crystallographic directions of the 112 classification are beginning to enlarge. At pressures of the order of 10^{-11} mm, the pattern was as badly contaminated after only two hours.

C. Measurement of the High Voltage. The high voltage necessary for this experimental problem was supplied by an rf high-voltage power supply constructed according to the design of Mautner and Schade (12). The high-voltage measurement was made across a 10-megohm potential divider with a Leeds and Northrup type K potentiometer. The entire potential divider was immersed in oil in order to eliminate resistance fluctuations caused by temperature changes.

D. Measurement of the Total Field-Emission Current. Because the shape of the point cathodes can be altered by drawing high field-emission currents which heat the points, the field-emission currents were kept to a minimum during this research. Since the largest total collection current was approximately 5×10^{-7} amp, a galvanometer was used for the current measurement. This galvanometer, which had a sensitivity of 1.25×10^{-9} amp/cm, was connected into the circuit with a 25,000-ohm Aryton shunt.

E. Measurement of the Phosphor Potential on Tubes of the Conventional Design. As stated previously, the first tubes which were constructed in this research had a separate anode structure to which the high voltage was applied. Before any analysis of photometric data could be attempted, it was necessary to know the actual potential of the

phosphor. This measurement was accomplished by means of a Compton quadrant electrometer connected as shown in the circuit diagram in Fig. 4. A circular spot of aquadag approximately one centimeter in diameter was painted on the outside of the glass envelope at the position where the potential of the phosphor was to be measured. This aquadag was then connected into the circuit as indicated. A stream of hot air was directed at the spot, and the heat was controlled so that the glass under the aquadag was brought to a temperature of approximately 100°C. This temperature caused the glass to be sufficiently conducting for the required measurements.

A high voltage v_1 was applied between the point cathode and anode. This applied voltage caused the phosphor to assume a potential negative with respect to ground. With the lead from the aquadag grounded, there was no deflection of the electrometer; but when a resistance was connected, a deflection was produced. The voltage v_2 was then increased until there was no deflection of the electrometer. At this setting, v_2 represented the potential difference between the phosphor and anode for the particular setting of v_1 . Both potentials, v_1 and v_2 , were furnished by regulated high-voltage power supplies and were measured across potential dividers with a potentiometer.

F. Photometric Measurement of the Relative Field-Emission Currents Along the Crystallographic Directions. The photometric method of measurement was accomplished by the use of a 931-A photomultiplier tube to measure the light output from the phosphor. In such a technique, the currents produced in the photomultiplier are directly proportional to the field-emission currents, provided two conditions are fulfilled: The light output from the phosphor must be directly proportional to the field-emission currents striking it; and the currents produced in the photomultiplier must be proportional to the light intensity falling on it. The latter is true for a 931-A if the current produced in the photomultiplier tube is less than 250 μ a. Nottingham (13) has shown that the first condition is true for willemite and ZnS:Ag, provided the electron current density striking the phosphor is less than one microampere per square centimeter. Hence, both requirements could be met easily in this research.

The currents produced in the 931-A photomultiplier were measured by a null-method circuit shown schematically in Fig. 5. The switch in the grid circuit of the 6SF5 was closed, and the galvanometer was brought to zero deflection with the zero adjustment. When the switch was opened, the current in the 931-A photomultiplier produced a voltage across the 10-megohm resistance. This voltage changed the bias of the 6SF5 and caused the galvanometer to deflect. The voltage across the 10-megohm resistance was balanced by a bucking potential, and the galvanometer returned to zero deflection. Measurement of the bucking potential with a Leeds and Northrup type K potentiometer then gave the value of the current produced in the photomultiplier.

The photomultiplier housing was completely light-tight, and the area immediately surrounding the 931-A was painted black to eliminate effects from scattered light. The field-emission tube and photomultiplier housing were surrounded by black cloth, and all

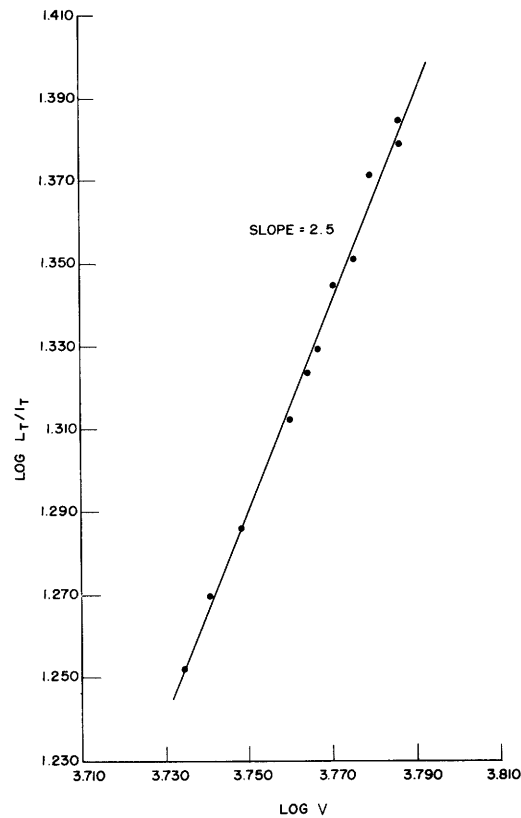


Fig. 6

Plot of log (light output per unit current) against log (phosphor potential) for tube with ZnS:Ag phosphor.

phosphor, V is the potential of the phosphor, and k and n are constants. The value of n varies with the type of phosphor, and it may vary to a smaller degree for different samples of the same phosphor.

In order to analyze the photometric data obtained in this research, it was necessary to determine the value of n for the particular samples of phosphor used. The total field-emission current I_T could be determined as a function of the phosphor potential with the use of a galvanometer. Therefore, if the total light output L_T (or something proportional to the total light output) could be determined as a function of the voltage, $\log L_T/I_T$ could be plotted against $\log V$, and the slope of the best straight line through the plotted data would give n .

The required measurement was made with an integrating box. This box was made from two one-gallon cardboard ice cream containers the interiors of which were sprayed with aluminum oxide to give a surface which reflected light diffusely. The integrating box was mounted so that the spherical projection tube was completely enclosed except for a small hole $3/8$ inch in diameter. A piece of white paper backed with black paper was pasted on the surface of the projection tube, and this paper was focused through the

3/8-inch hole on the aperture of the photomultiplier housing. The black backing eliminated transmission of light through the paper, and all light from the surface of the white paper was light from the field-emission pattern reflected from sides of the integrating box. Measurements of the light from the paper were therefore proportional to the total light output from the field-emission pattern.

Data obtained from the final experimental tube with a ZnS:Ag screen are shown in Fig. 6, and the slope of the best straight line is 2.5. Data were also obtained for a tube with a willemite screen, and the value of n was found to be 2.0. These values agree quite closely with those previously obtained by Nottingham.

H. Determination of the Radius of the Point. The value of the radius of the point cathode was necessary for calculating the electric fields and the current densities. This value was obtained by observations of the point under an optical microscope of 1000 magnification. The point appeared to be perfectly smooth with no noticeable irregularities, and the radius of curvature was approximately one micron. An attempt was made to observe the point under an electron microscope, but unfortunately the point was broken when it was mounted.

III. Experimental Results

A. Presentation of Experimental Data. In order to determine the value of electric field in a tube of this type, Benjamin and Jenkins (14) made a study of the equipotentials produced by a model of the point and filament system on a rubber member. They found that the electric field at the surface of the point cathode is given by

$$F = \frac{1}{2} \frac{V}{r} \quad (3)$$

where F is the electric field, V is the potential of the spherical envelope, and r is the radius of the point. The field-emission equation as applied to a uniform surface should give a straight line for a plot of $\log J/V^2$ against $1/V$, since the electric field is proportional to the applied potential. Even though the total emission from a point is the sum of the emission from elements of nonuniform surface, the total current divided by the square of the potential may be used in a plot as illustrated in Fig. 7. The results are well represented by a straight line over the range of current and voltage used.

Figure 8 shows typical field-emission plots which were obtained by photometering some of the main crystallographic directions. These data are also plotted with respect to applied voltage instead of electric field. The currents are arbitrarily plotted in terms of the current produced in the 931-A photomultiplier tube. To indicate that these currents actually represent the light output of the phosphor, the symbol L is used. Experiments using the integrating box had shown that the light output per unit current for the zinc sulphide phosphor was proportional to $V^{2.5}$. Therefore, it was necessary to plot $\log L/V^{4.5}$ against $1/V$. Slopes of the straight lines are indicated in parentheses.

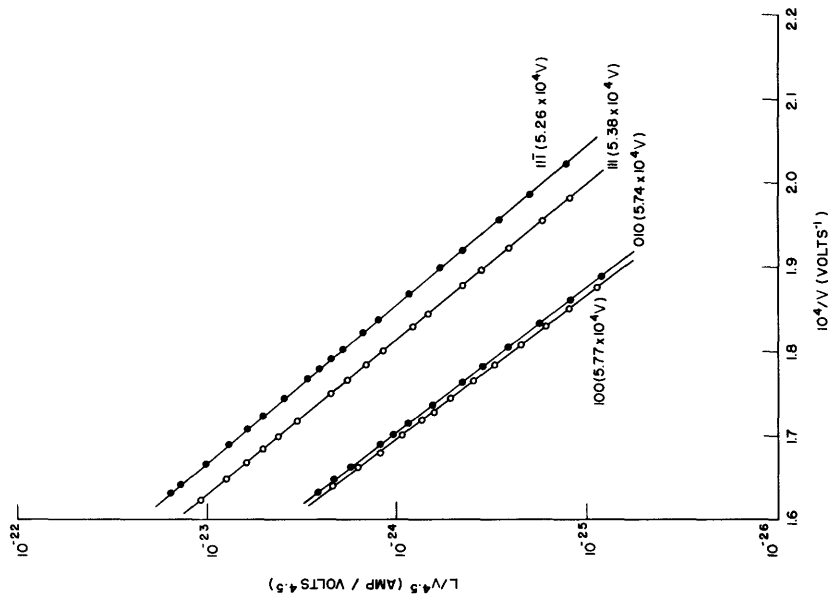


Fig. 8

Field-emission plot for 100, 010, 111, and 111 crystallographic directions.

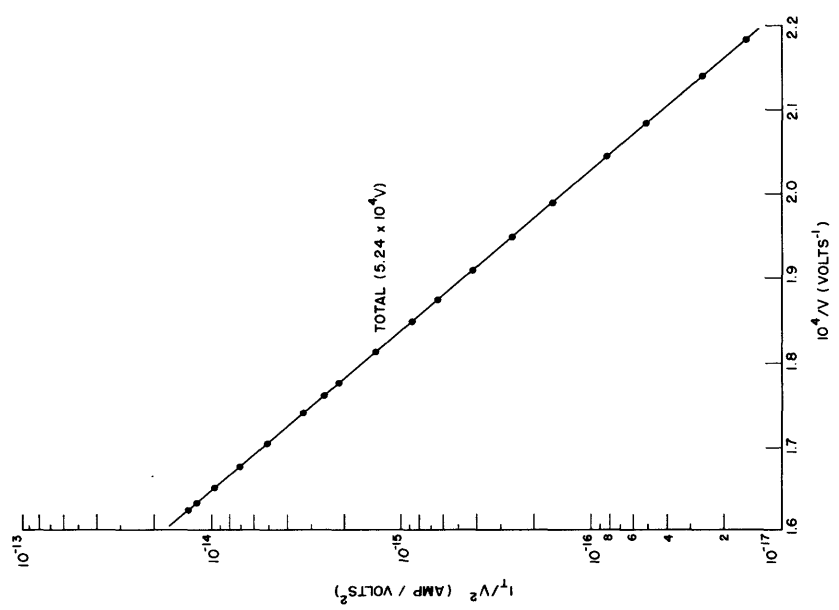


Fig. 7

Field-emission plot for total emission current.

Excellent straight lines were obtained for all the crystallographic directions which were photometered. These data were completely reproducible, indicating that the vacuum in the tube was sufficiently good to make contamination of the point negligible during the time data were taken. Sufficient measurements were made to establish a definite straight line, and photometric data from the darkest spots on the pattern were taken over almost two orders of magnitude of current.

B. Discussion of Experimental Data. When a comparison of the field-emission plots for the various crystallographic directions is made, consideration must be given to the fact that these are not true field-emission characteristics. The plots are made with respect to the applied voltage, and the electric field at the surface of the point for a given voltage may be different for the various directions. It is evident from the field-emission equation that if the field is different, the absolute magnitude of the currents will be different. However, it should be emphasized that a difference in field also affects the slope of the straight line. A very good example of this effect is indicated in Fig. 8 where data are plotted for the 111 and $11\bar{1}$ crystallographic directions. Since these two directions are essentially the same, they have the same value of work-function. Consequently, the magnitudes of the emission currents should be the same, and the slopes of the straight lines should be equal. This is not the case. The absolute magnitudes of emission current differ by approximately 40 percent, and the slopes differ by approximately 2 percent. A 2-percent difference in electric field between the two directions would account for these differences.

A similar comparison of the data for the other crystallographic directions leads to an interesting conclusion. Except for directions of the 112 classification, directions of a certain Miller Index classification had the same slope within less than 1 percent. Furthermore, the absolute magnitudes of the currents were very nearly the same. However, for directions of the 112 classification, the data indicated an electric field at the point for the $12\bar{1}$ and $21\bar{1}$ directions, which was approximately 2 percent higher than that for the 121 and 211 directions. Reference to Fig. 1(b) shows that the $12\bar{1}$, $21\bar{1}$, and $11\bar{1}$ crystallographic directions are grouped together on the opposite side of the point from the 121 , 211 , and 111 directions. Therefore, it is reasonable to assume that the shape of the point was slightly different on the two sides. Perhaps there was a somewhat smaller radius of curvature on one side of the point which made the electric field approximately 2 percent greater. These data, therefore, indicate that the emission current from the surface of a smooth point is largely dependent on the general curvature of the point. Any effects which are caused by irregularities of atomic dimensions must be reasonably small.

There are other general statements that can be made concerning the data. Since these statements are based for the most part on a comparison of the slopes of the straight lines, these slopes are tabulated in table I. Only one direction of each Miller Index classification is listed, since with the assumption of a slightly higher field at one

section of the point cathode, the slopes for similar crystallographic directions agree very closely. The values of work-functions for the crystallographic directions which were determined by Nichols, and by Mendenhall and DeVoe, are also tabulated.

These data show that the crystallographic directions that are represented by dark spots on the field-emission pattern (110, 121, and 100) are the three with the highest values for the slope. Furthermore, the percentage difference in the slopes for the various directions is sufficiently small so that it may be explained by the difference in work-function determined by other methods. The slope of the straight line for the total field-emission current would be expected to be greater than that for the bright spots and less than that for the dark spots. In general this is true, since the value of the slope for the total current plot is 5.24×10^4 volts.

C. Plots of Field-Emission Characteristics.

1. Assumption of electric field distribution. A complete analysis of the data could not be made unless true field-emission characteristics could be plotted. These plots required a knowledge of the distribution of electric field around the tip of the point cathode. Since this field distribution was not known, a distribution which appeared logical was assumed, and the analysis was based on this assumption.

Photometric data were taken for the 112 crystallographic direction. These data should have given a plot which was identical with those of the other directions included in this Miller Index classification. However, the field-emission plot indicated that the electric field for the 112 direction was approximately 5 percent less than the field for the 121 direction. The angles which these crystallographic directions made with the axis of the point cathode were calculated with the assumption that the 110 direction was along the axis. This assumption appears valid since tungsten wires are drawn with the 110 direction along the axis of the wire. The 121 crystallographic direction occurred at an angle of 30° from the axis while the 112 direction was at an angle of $54^\circ 44'$. Hence, there was an average decrease in electric field of 1 percent every 5° . This variation was assumed to be uniform and to occur at angles less than 30° .

It is admitted that the data for the 112 crystallographic direction are not very accurate. These data extend over a range in current of approximately only one-half an order of magnitude, and the photometric currents were so weak that they were difficult to measure accurately. However, it is believed that the data give a reasonable basis on which an electric field distribution could be assumed.

The absolute magnitude of the electric field for the total emission current was calculated from Eq. 3. Since the total field-emission current was influenced by the average electric field over the surface of the point, the result of this equation must represent an average field. The field-emission patterns had indicated that no appreciable emission came from directions making angles larger than 60° with the axis of the point cathode. Hence, the value of electric field given by Eq. 3 was also assumed to represent the field at the point for the crystallographic direction making an angle of 30° with the axis.

The fields for the other directions were modified accordingly. Table II lists the angles of the various crystallographic directions and the amount by which the electric field at each direction was modified to correspond to the assumed electric field distribution.

2. Conversion of units.

a. Conversion of units of light output into units of current. The conversion of units of the photometric data required a calibration whereby the arbitrary units of current through the 931-A photomultiplier could be changed into units of current striking the phosphor. Since the total emission current was known, this calibration could be made if the total light output from the phosphor was known in terms of the arbitrary units. This determination of the total light output was made by a process of numerical integration. The field-emission pattern was divided into about twenty-five sections which presented approximately the same brightness to the eye. Many of these sections had been photometered previously as specific crystallographic directions. The others were photometered at sufficient voltages to determine the relationship between light output and voltage, and the light output from each section was determined for the particular voltage at which the calibration was made.

It is admitted that such a numerical integration is not very accurate. However, the important considerations in the experimental results involve a comparison of the relative emission currents along the various crystallographic directions, and these relative data are unchanged by a conversion of units. Furthermore, it is not likely that the error in conversion will exceed 25 percent, so that at least the general magnitude of the currents is obtained.

b. Determination of the surface area emitting. In order to determine the current densities for the field-emission characteristics, it was necessary to know the value of the surface area which was emitting. The point was assumed to be semi-spherical, and the total surface area emitting was calculated on the basis that no emission took place from crystallographic directions which formed an angle greater than 60° with the axis of the point cathode. The surface area contributing to the emission along the crystallographic directions was calculated from a knowledge of the radius of the point, the radius of the glass bulb, and the size of the aperture in the photomultiplier housing.

3. Analysis of field-emission characteristics. The field-emission characteristics which are plotted in Fig. 9 resulted from the conversion of units and the assumption of the electric field distribution. The field-emission characteristic for the total current lies between the plots for the dark areas and light areas. This is an indication that the magnitude of the current densities for the various crystallographic directions is reasonably correct even though the procedure used to convert units was not very accurate.

The field-emission equation can be written in the form

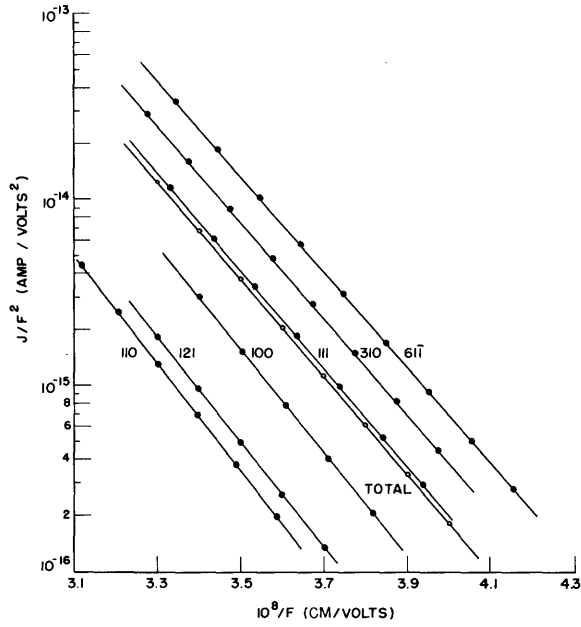


Fig. 9
Field-emission characteristics.

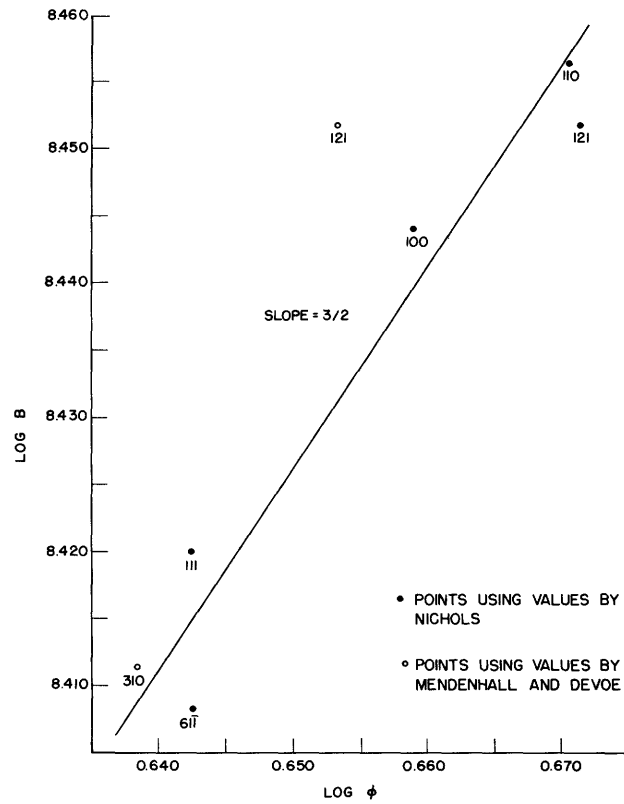


Fig. 10
Plot of log (slope of field-emission characteristic) against log (work-function).

$$\log \frac{J}{F^2} = \log A - \frac{B}{F} \quad (4)$$

where B is the slope of the field-emission characteristic and log A is the intercept when $1/F$ is zero. Table III gives the values of log A and B for the data obtained in this research. The values of the work-functions as obtained by Nichols and by Mendenhall and DeVoe are listed for comparison. As a matter of general interest, the values of current density are tabulated for an electric field of 3.0×10^7 volts/cm.

The values of B are seen to vary in the same general manner as the values of the work-functions obtained by other methods. According to the field-emission equation, a plot of the logarithm of B against the logarithm of the work-function should give a straight line of slope $3/2$. The data are plotted in Fig. 10, and the straight line which is drawn with a slope of $3/2$ represents the data quite well.

This plot is not given as a definite proof of the $3/2$ power of the work-function in the field-emission equation. It merely indicates that with a reasonable assumption of the electric field distribution around the point cathode, the experimental data are in agreement with existing values of the work-function and the theoretical field-emission equation.

IV. Conclusions

This research has shown that a field-emission projection tube can be evacuated to such an excellent vacuum that quantitative measurements can be made without experiencing difficulties due to contamination of the point cathode. The conventional field-emission projection tube is satisfactory for qualitative investigations but is unsatisfactory for quantitative measurements. Photometric data indicate that the dark spots on a field-emission pattern of clean tungsten are caused by the difference in the work-functions of the crystallographic directions. Furthermore, with a reasonable assumption of the electric field distribution around the surface of the point cathode, the data are in agreement with the theoretical equation.

V. Acknowledgment

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Table I

Values of Slopes of Field-Emission Plots and
Previously Determined Values of Work-Function

Crystallographic Direction	Slope (volts)	ϕ_N * (ev)	ϕ_{MD} ** (ev)
110	5.43×10^4	4.68	
121	5.71×10^4	4.69	4.50
100	5.77×10^4	4.56	
111	5.38×10^4	4.39	
$61\bar{1}$	5.21×10^4	4.39	
310	5.16×10^4		4.35

*Values of work-functions determined by Nichols.

**Values of work-functions determined by Mendenhall and DeVoe.

Table II

Variation of Electric Field with Crystallographic Direction
Based on the Assumed Electric Field Distribution

Crystallographic Direction	Angle with Axis* of Point Cathode	Variation in Field from the Value $F = \frac{1}{2} \frac{V}{r}$
110	0°	+6 percent
121	30°	0 percent
100	45°	-3 percent
111	35° 16'	-1 percent
$61\bar{1}$	36° 34'	-1.3 percent
310	26° 34'	+0.7 percent

*These angles are actually angles between the 110 crystallographic direction and the other crystallographic directions listed.

Table III

Slopes and Intercepts of Field-Emission Characteristics

Field-Emission Characteristic	Log A	B* (volts/cm)	ϕ_N (ev)	ϕ_{MD} (ev)	J** (amp/cm ²)
110	-5.45	2.86×10^8	4.68		0.95
121	-5.40	2.83×10^8	4.69	4.50	1.31
100	-5.09	2.78×10^8	4.56		4.05
111	-5.18	2.63×10^8	4.39		10.3
611	-4.91	2.56×10^8	4.39		32.1
310	-5.08	2.58×10^8		4.35	18.6
Total Current	-5.26	2.62×10^8			9.16

* (Note added by W. B. Nottingham) These values of B depend on the numerical value of the point radius r and the validity of the factor $(1/2)$ in Eq. 3. There are reasons to believe that both this factor and the point radius should have been smaller. If there is a residual error, it enters as a constant factor applicable to all of these values of B.

** These values of current density occurred for an electric field of 3.0×10^7 volts/cm. The high voltage required to produce this field varied for the different directions, but it had an average value of 6000 volts.

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