I. PHYSICAL ELECTRONICS

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A. ELECTRON-EMISSION PROBLEMS

1. Thermionic Work Function and Conductivity of Oxide-Coated Cathodes

Measurements of conductivity and thermionic emission are being taken on an oxide-coated cathode to determine the energy levels present in (Ba, Sr)O. The three methods of conductivity determination now in use are: 1) drawing probe current as a function of probe voltage, 2) drawing emission current and observing probe voltage, and 3) measuring the current across a gap in the pure nickel base metal as a function of applied voltage. Data are taken at various temperatures and in different states of activation.

After converting the carbonates to the oxides and before drawing emission current, the thermionic work function was 3.15 ev and the conductivity activation energy was 1.91 ev as determined by the gap method over a temperature range from 780° K to 939° K. In this inactive state, probe measurements were very difficult and yet a rough indication yielded 2.1 ev for the conductivity activation energy by the probe current method. The cathode was slowly activated by drawing emission current. Successive Richardson plots showed the gradual changing of the thermionic work function from 3.15 to 1.82 to 1.56 to 1.38 with A values decreasing in the same direction. In the present activated state, preliminary gap conductivity values yield 1.31 ev for the activation energy over the temperature range of 445° K to 811° K. Between 445° K and 306° K a minimum appears in this curve similar to that observed in germanium. Since this is a preliminary curve that has not been rechecked, no great significance can be attached to this straight line deviation; but the possibility of prominent lattice and impurity scattering in this temperature range could infer a constant number of carriers as in germanium.

Probe measurements are under way for this active state. When probe voltage is taken as a function of emission current, the probe becomes negative at currents in the microampere region. A good explanation of probe action here is lacking and more results are needed to reveal the true nature.

R. T. Watson

2. Fine-Grain Oxide-Coated Filaments

Thermionic emission measurements have been made on a polished single-crystal tungsten filament coated cataphoretically with equimolar barium and strontium oxides. The following types of data were taken: Projection tube measurements, Richardson data, retarding potential data, accelerating potential data, and X-ray diffraction patterns of the coating.

The projection tube measurements were undertaken to assess the effect on emission of the crystallographic structure of the base metal. Cylindrical projection tubes were used, and patterns were photographed with the bare wire and with the same wire after coating with oxides. No evidence was found in the emission from the oxide-coated wires of variations of emission which could be correlated with the variation of work function with crystallographic direction of tungsten.

The Richardson retarding potential and accelerating potential data were taken with a third tube which was designed to approach as closely as possible the ideal conditions assumed by Schottky (1, 2) in his derivation of the equations for the thermionic emission of electrons under retarding and under accelerating fields. These assumptions, and the means used to approach them, were:

a. That the anode and the cathode should be infinitely long. The anode system consisted of a collector located between two guard rings. All three of these elements were kept at ground potential.

b. That there should be no effect of space charge. In all measurements the currents were so low that space charge effects could have taken place over a potential range from zero-field of less than 0.01 volts.

c. That there should be no potential drop along the cathode. The filament was heated by pulses, and the thermionic measurements were made between pulses.

d. That the anode should not have a "patchy" surface. It is known that tantalum anodes, in the presence of oxide-coated cathodes, become contaminated by the oxides in such a way that they exhibit small areas of low work function. This difficulty was avoided by designing the tube with two anodes. The main anode was moved away from the oxide-coated surface during conversion and activation. At this time current was being collected by the auxiliary anode. When measurements were to be made, the main anode was slid into position.

e. That there should be no change in the state of activation of the cathode during measurements. To achieve this end the temperature was kept low (usually below 600°K), and the maximum current density was no higher than 1 μa per sq. cm.

f. That there should be no reflection of electrons at the anode. Such a reflection effect would influence data more strongly if the anode and cathode radii were comparable. To reduce the influence of anode reflection effect, a filamentary emitter was used.

The other variations from ideality are fundamental to the cathode and would appear in the data as deviations of experimental curves from the two Schottky equations. The deviations might be due to a patchy cathode, to reflection, and to a potential drop through the cathode coating.

The Richardson data showed a work function of 1.31 volts and an A-value of 0.048 $amps/cm^2$-$degree^2$. These values are comparable with those found by other workers.

The Schottky plots were taken at temperatures of 514°K, 537°K, and 563.2°K. The curves showed a rapid rise for applied fields up to about 2.5×10^5 volts per meter, then a linear portion running to about 2.5×10^6 volts per meter. The slopes of the linear portions of the curves were higher than expected from mirror-image theory by a factor of about 3.

The rising part of the plots could be well explained using Nottingham's (3) strip theory, with a patch size of 2×10^{-6} meters, and a peak-to-peak variation of patch work-function of 0.4 volts.

The fact that the linear portions of the Schottky plots were high by a factor of 3 was explained as due to surface irregularities of the oxide. Thus the field at the cathode is higher than the applied field by a factor of 9.

The retarding potential data differed considerably from theory. When compared with theory, the experimental plots were much more rounded and were shifted toward accelerating potentials. The effect was much more pronounced than could be explained by patches or by reflection. It was assumed that the anomalous curves were due to a potential drop (V) through the coating, caused by a high resistance interface layer. At each value of observed current the displacement of the voltage actually applied, compared with the estimated voltage which should have given the current, was taken to be the "iR" drop (V) through the coating.

On the basis of this assumption, i-V curves were computed. These plots showed nonlinearity in that di/dV increased for increasing emission current. The nature of the experiment precluded taking data for the reverse direction of current, but the curvature suggested rectification such that the easy direction of electron flow would be from the base metal to the oxide. Such rectification would occur at the metal-to-oxide boundary if the oxide were a P-type semiconductor at the temperatures used. This conclusion is given some weight by the results of Wright (4) who found a coating of (BaSr)O to be a P-type semiconductor at temperatures below 850°K.

From the slope of the i-V curves near V = 0, the conductivity of the coating was computed, assuming the potential drop to take place through the total coating thickness. The logarithm of the computed conductivity was plotted as a function of 1/T and was found to yield a straight line. The slope of the line indicated a barrier height of 1.3 volts.

Although no data were available on the conductivity of the interface materials expected in the present cathode, these results were compared with those of Eisenstein (5) on an interface of Ba_2SiO_4. His data, when extrapolated to 600°K, gave conductivities running from 10^{-11} to 10^{-14} mho/cm. These results compare well with those of the present experiment which gave a conductivity of 5×10^{-12} mho/cm at 585°K.

Since the evidence indicated strongly the presence of an interface, an X-ray analysis was made of an emitter prepared in a manner similar to the one under discussion. A sample of the filament was mounted in a Debye camera and was rocked during a 12-hour exposure to copper Kα radiation. The analysis positively identified the presence of

$BaWO_3$ and indicated the probable presence of $(BaSr)WO_3$. These compounds had already been found in an oxide-coated tungsten cathode by Affleck and Hensley (6).

Results of this work will be presented in more detail in a technical report.

References

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C. P. Hadley

3. Magnetic Velocity Analyzer Investigation of Thermionic Work Functions of Single-Crystal Tungsten Filaments

A new method is to be employed in obtaining thermionic data from single-crystal tungsten filaments. It is hoped that this method will yield quantitatively the differences of work function and also the variation with temperature of the differences of work function between the crystal faces of a single-crystal filament. Since the "apparent" thermionic work function and emission constant obtained by taking the slope and the intercept of a Richardson plot each contain the temperature derivative of the true work function, a knowledge of the temperature variation of the work function might be used in conjunction with existing Richardson data to obtain a close approximation to the "true" work functions and emission constants.

The basic experimental arrangement is to consist of a single-crystal tungsten filament capable of being rotated about its own axis. The filament will be surrounded by a concentric cylindrical anode having a narrow, longitudinal slit in one side. The slit will enable electrons emitted in a single direction from the filament to enter a magnetic velocity analyzer. This entire apparatus will be sealed off at high vacuum in a glass envelope. With the omission of the ionization chamber, the arrangement is similar to that used by W. B. Nottingham in measuring the ionization probability in mercury vapor (see Phys. Rev. 55, 203; 1939).

By comparing the energy of the electrons as obtained from the magnetic field and the geometry of the analyzer with the applied potential of the analyzer with respect to the filament, one can obtain the effective contact difference of potential between filament and analyzer. The variations in the contact potential with rotation of the filament should give the differences of work function corresponding to different crystallographic directions. The temperature coefficients of these work functions could be obtained by varying the filament heating current.

Calculations of the electron trajectories in the tube have been made and have led to the establishment of the important dimensions of the tube (analyzer radius, anode radius, and slit widths).

Some experimentation has led to a satisfactory method of rotating the filament with gravity.

Crystallization of tungsten filaments (polishing the wire to remove the die-marks, and heating it slowly in a cylindrical projection-tube) has been started.

A. R. Hutson

4. Determination of the Field-Emission Properties of Single Tungsten Crystals by a Photometric Method

Previous experimental investigations of field emission may be classified into two general groups: quantitative measurements to determine the applicability of the theoretical Fowler-Nordheim equation; qualitative observations of contamination and migration with the field-emission projection tube. Certain aspects of the theoretical equation have been proved, but one point still not verified is the form of dependence of the current density on the work function. Results by Haefer agree with the theory and indicate that the current density depends exponentially on the 3/2 power of the work function, while results by Müller require the third power. 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. Such a pattern portrays bright and dark spots which can be associated with emission along the various crystallographic directions, but no satisfactory explanation has been given for the relative values of emission.

The problem undertaken in this research was a study of the relative values of field-emission current density along the various crystallographic directions. This study was made with a field-emission projection tube so that the state of cleanliness of the tungsten point cathode could be known from the pattern. Light from the main crystallographic directions was photometered while the electric field was varied, and the data were analyzed by the Fowler-Nordheim equation.

The problem of attaining the ultimate in high vacuum was solved in a rather unique manner. Previous research had indicated that with the use of getter, when a field-emission projection tube is sealed off, the vacuum is not satisfactory. Hence no getter was used. The tube was processed very thoroughly on the vacuum system with several cycles of outgassing and baking. Then, at seal-off, an ionization gauge was sealed off with the experimental tube, and the operation of the ion gauge served to clean up the residual gases. In this manner patterns of clean tungsten, which remained stable for several hours, were obtained on two different tubes. Flash-filament data on a conventional ion gauge with one tube indicated a residual pressure of about 10^{-12} mm of Hg.

This was essentially confirmed on the next tube, since the pressure was found to be less than the X-ray limit of an ion gauge of the new design. On this particular gauge, the X-ray limit was 3.8×10^{-11} mm of Hg.

The first two tubes were constructed according to the conventional design for field-emission projection tubes. This design involves the use of a separate anode structure to which the high voltage is applied. The potential of the phosphor then depends on the secondary-electron-emission properties of the phosphor and the efficiency of collection of these secondary electrons by 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 secondary-electrons emitted from the phosphor. Although this condition was fulfilled on the second tube, the tube was unsatisfactory for quantitative measurements. The potential of the phosphor 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 potentials made it impossible to make a satisfactory analysis of the photometric data which were obtained.

A third 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. The voltage was applied directly to the spherical surface and thereby eliminated the difficulties experienced with tubes of the conventional type. Photometric data of the relative emission currents from the various crystallographic directions were taken, and the total emission current from the point cathode was measured by normal electrical methods. These data were analyzed according to the Fowler-Nordheim equation, except that the applied voltage was used instead of the electric field. Necessary corrections were applied to account for the fact that the light output per unit current from the phosphor was not independent of the phosphor potential. The resulting plots were excellent straight lines. In general, the dark areas of the emission pattern were crystallographic directions for which the slope of the plotted line was higher than that determined for the total emission current, while the bright areas represented crystallographic directions for which the slope was lower than the average. If the theoretical equation was assumed to be correct, the extreme difference in the slopes predicted an extreme difference in the values of work function which agreed very well with the values determined by Nichols. An assumption, based on experimental data, was made concerning the distribution in electric field over the surface of the point cathode, and true field-emission characteristics were plotted. The logarithm of the slopes of these characteristics was plotted against the logarithm of the work function values determined by Nichols and by Mendenhall and DeVoe. The resulting plot indicated that a straight line with a slope of 3/2 would fit the data quite well. The results of this research are therefore in accord with the Fowler-Nordheim theory and are not in agreement with the empirical result of Müller.

This research problem has been completed. An account of the complete research will be published in a technical report. M. K. Wilkinson

5. Photoelectric Emission

The experimental tube designed for the study of the photoelectric properties of molybdenum as they are influenced by the deposition of germanium has been constructed and its vacuum processing is nearly completed. A more detailed description of the tube is given in the Quarterly Progress Report, July 15, 1950. Difficulties associated with tube processing have delayed the finishing of the tube. All metallic parts were prebombed at 2000°C before being placed in the tube and were bombed at 1200°C between each of five bakes. The pressure with the tube on the vacuum system is 6×10^{-9} mm Hg.

The cadmium and mercury ultra-violet light sources have been constructed. These sources consist of an 8-cm long, 2.5-cm diameter quartz tube filled with argon at a pressure of 10 mm Hg and an amount of cadmium or mercury equal to the amount of that material in the vapor phase at 500°C. The cathodes are thorium, fused into the turns of closely coiled tungsten and connected to tungsten-to-quartz presses at either end of the quartz tube. This type of cathode furnishes the current required for an arc discharge. This quartz tube is placed inside a pyrex envelope containing a quartz window. The space between the two tubes is evacuated and filled with argon at a pressure of 10^{-3} mm Hg. It has been found that air cooling of the quartz-to-tungsten presses will crack the quartz when the arc is stopped; thus the need for an envelope and a reduced pressure in the region between the tubes. H. S. Jarrett

6. Photoelectric Emission from Quartz

The photoelectric properties of metals have been widely studied and many of the fundamental aspects are well understood. Very little work has been done on the surface photoelectric properties of insulators. This new project is being started along lines that are so new that it is not certain that positive results can be obtained. An outline of this new method of investigation is given.

The purpose of the experiment is to measure the "surface state" energy levels for electrons on a polished crystal quartz surface. The proposed method is to charge the test surface to a known potential by subjecting it to a beam of electrons from the gun (see Fig. I-1). During this charging period, a metal electrode on the back surface of the test plate is held at ground potential. When the charging has gone to a potential determined by the accelerating voltage, the electron gun is turned off and the electrode is switched from ground to an electrometer. The surface is now ready for illumination. If the incident radiation has sufficient energy to remove electrons from the surface, this

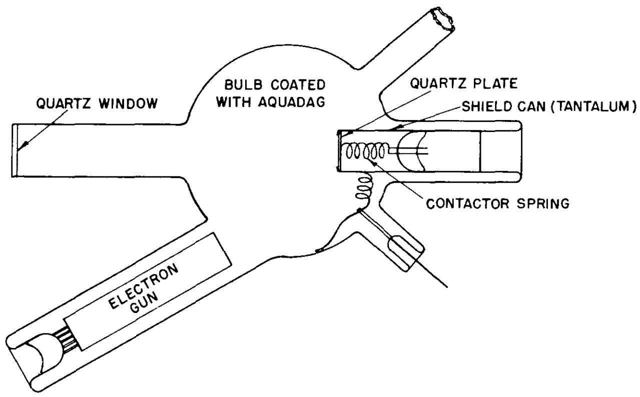

Fig. I-1 Experimental tube for measuring the photo-emissive properties of quartz.

fact should be indicated by an electrometer deflection. It is hoped that the long wavelength threshold for this sort of photoelectric emission can be determined as a function of the potential to which the surface has been charged.

The experimental tube is completely constructed and has gone through most of the evacuation process.

D. Jeffries

B. STUDIES WITH GASEOUS DISCHARGE

1. Investigation of Low-Pressure Mercury Arcs

The new tube not previously described in detail for the study of a low-pressure arc in mercury has been completed and tested.

The electron energy distribution found in the tube was in every way similar to the distributions reported previously. These distributions are nearly Maxwellian but do have a deficiency of high energy electrons. This deficiency of high energy electrons seems to be closely associated with the electron energy loss at the walls of the tube for very low pressures, whereas, as the mercury pressure is increased until the mean-free-path of the electrons is small compared with the dimensions of the tube, the deficiency in high energy electrons is probably the result of inelastic excitation collisions with the mercury atoms.

A movable probe was used to obtain the variation in potential and in electron and ion concentration as a function of the radial distance across the tube. The distribution of potential found agreed qualitatively with those distributions found in the previous tube but differed quantitatively in such a manner as to throw some doubt on the conclusion that the observed distribution was in rather exact agreement with the diffusion theory. The exact status of this theoretical analysis of the experimental results can be established only after additional work has been done on the detailed examination of the experimental results.

For the time being experimental work will be discontinued in this field. A complete technical report is being prepared.

R. M. Howe (written by W. B. Nottingham)

C. EXPERIMENTAL TECHNIQUES

1. Spectral Emissivity in Tungsten

In spite of the very considerable effort having been applied toward the production of a new experimental tube for the study of the spectral emissivity of tungsten, failures in one respect or another have interfered with the completion of this tube. The latest efforts have overcome some of the difficulties that caused previous failures. A new technique has been developed for the production of the specimen. At one time it was thought that the best way to produce the weld between the thin wall of tungsten and the supporting tungsten lead was to arc-weld it. This method of making connection was very difficult and has now been replaced by a spot-welding process. The new feature which seems to make the spot-welding process more successful than was our previous experience is that the tungsten leads have been etched by an electrolytic process to produce a rough mat surface. The electrode structure has also been redesigned so that the current-carrying leads expand symmetrically and a spring mounted in the tube will permit the specimen to expand upon heating without bending.

W. B. Nottingham, L. E. Sprague, H. R. Philipp

2. Ionization Gauge Studies

For a long period of time we have been investigating the design of ionization gauges which would minimize the interfering effect caused by the "X-ray effect" that sets a limit on the best vacuum that can be measured with an ordinary gauge. This limit usually lies close to 10^{-8} mm. A new gauge design patterned according to the general principles of Alpert and Bayard (see Rev. Sci. Instr. 21, 571, 1950) has been tested and found to give excellent results down to about 5×10^{-11} mm but has an X-ray limit at about half this pressure. Other modifications are being studied which it is hoped will carry at least to 10^{-12} mm and will be reported on as progress in their study is made.

W. B. Nottingham