I. PHYSICAL ELECTRONICS

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A. ELECTRON-EMISSION PROBLEMS

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

By measuring the thermionic emission from an oxide cathode together with the conductivity through the oxide coating, an experimental study of the semiconductor energy-level model of (Ba, Sr)O is being made. Since the energy levels apparently vary with the degree of activation of the cathode, treating the oxide with methane and oxygen will add several degrees of freedom to the present research.

The tube being used for this study has been completely assembled and attached to the vacuum system. Since a vacuum of better than 10^{-8} mm Hg may be present, a Bayard-Alpert ion gauge has been sealed onto the system along with the main tube. This gauge will detect a vacuum as low as 10^{-11} mm Hg at various stages of tube processing. Three batalum getters are enclosed in the tube. The getters and the crackable glass tips make it possible to open the tube to the vacuum system for gas treatment after having sealed it off. A batalum getter is purer than other getters and is relatively free of migrating elements which would tend to increase the leakage in the tube. The leakage resistance is being measured at regular intervals.

Recently the vacuum system was modified to allow for the admission of high-purity oxygen and methane on the low-pressure side of the mercury pumps. Since it is very difficult to admit purified commercial methane from a lecture bottle without also admitting a small amount of air to the system, steps are being taken to put up purified methane in a pyrex flask with a crackable tip to be sealed onto the vacuum system.

Although progress is being made in taking data, results are still in the preliminary stages and nothing definite can yet be concluded.

R. T. Watson

2. Fine Grain Oxide-Coated Filaments

The total emissivity of an oxide-coated tungsten filament has been measured over the temperature range 400°K to 1000°K. The emissivity found was lower than that usually reported. A minimum was found in the total emissivity at a temperature of 600°K.

In order to get data for use in temperature measurements, emissivity determinations were made on a filament of the type described in previous Quarterly Progress Reports. It will be recalled that these filaments were formed by cataphoretically coating a polished tungsten wire with barium and strontium carbonates. The carbonates were converted to oxides by the application of a heating current.

Experimental Procedure. In the present experiments a long wire was mounted in an evacuated bulb, and only a small central section of this wire was coated. A lead was welded at each end of the coated section so that the potential drop across it could be measured with a potentiometer. The heating current through the filament also passed through a standard 1-ohm resistor. A potentiometer was used to measure the voltage across this resistor. From this voltage, Ohm's law was used to calculate the heating current. From these data the resistivity and the power input per unit length were determined.

Temperature Determination. Various authors have published data on the resistivity of tungsten as a function of temperature (1, 2, 3). From these data the temperature of the oxide-coated filaments was determined, for the heating current is carried predominantly by the tungsten wire. There is a slight ambiguity in the temperatures so determined, for the several authors quoted above do not agree too closely in their published values of resistivity. In general, one is inclined to depend on the data of Langmuir and Jones (3) at higher temperatures, and on those of Langmuir and Taylor (1) at the lower temperatures.

Emissivity Determinations. The emissivity was calculated from a modification of the Stefan-Boltzmann relation:

$$P = E\sigma(T_f^4 - T_r^4)$$

where P = power radiated per unit area, E = total emissivity, σ = Stefan's constant, T_f = filament temperature, and T_r = room temperature. Since the heated filament was long, the temperature over the central section was taken as constant. Under these conditions, the power radiated per unit area is equal to the power input per unit area, and the latter calculated from the experimental data. The emissivity was then determined from the equation above. The total-emissivity results as obtained from a typical filament are shown in the following table. For series I, the total emissivity was calculated by using temperatures that depend on the resistivity data of Forsythe and Watson (2); for series II, those of Langmuir and Jones (3) were used; and for series III, those of Langmuir and Taylor (1) gave the temperatures.

Emissivity	T°K						
	400	500	600	700	800	900	1000
I	0.205	0.185	0.175	0.182	0.198	0.213	0.223
II	0.216	0.191	0.182	0.198	0.218	0.235	0.249
III	0.227	0.201	0.192				

C. P. Hadley

References

1. I. Langmuir, J. B. Taylor: J. Opt. Soc. Am. 25, 321 (1935).
2. W. E. Forsythe, E. M. Watson: J. Opt. Soc. Am. 24, 114 (1934).
3. I. Langmuir, H. A. Jones: G. E. Review 30, 354 (1927).

3. Deterioration of Oxide-Coated Cathodes under Low Duty-Factor Operation

This investigation has been completed, and will be covered in forthcoming Technical Report No. 159. It was found that when oxide cathodes coated on nickel cores containing about 0.1 percent silicon are operated without electron emission, they develop a high resistance in a layer of Ba_2SiO_4 located at the interface between the oxide and the core. The layer of Ba_2SiO_4 was found to be present not only in cathodes with interface resistance, but also in cathodes without interface resistance. The development of a resistance in this layer was found to be heavily favored by the absence of electron emission from the cathode during life. To account for these observations, it has been assumed that when the layer of Ba_2SiO_4 is formed during the process of activation of the cathode, a certain fraction of the stoichiometric excess of barium also formed at that time remains within the layer, providing it with donor centers which convert it from an insulator to an "excess" semiconductor, and cause it to have negligible resistance. Since these donor centers behave on the average as positive charges, their migration during life will depend on the presence or absence of an electric field in the interface region, and consequently on the presence or absence of electron emission from the cathode. A model based on these ideas appears capable of accounting for the experimental results.

J. F. Waymouth, Jr.

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

This research involves a study of field emission by a spherical projection tube. The experimental tubes which have been used up to the present time have had essentially the same type of construction. The spherical glass envelope was coated on the inside with a phosphor. The filament was an extremely sharp point etched electrolytically from tungsten wire, and the high voltage was applied to a circular tungsten anode surrounding the point filament. In this type of construction 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.

As stated in the Quarterly Progress Report, April 15, 1950, a tube was completed on which a satisfactory field-emission pattern was observed. Extremely careful vacuum techniques were employed, and a vacuum was attained such that the rate of adsorption of residual gases on the point was so slow that there was no noticeable change in the field-emission pattern over a period of several hours. Rough calculations based on the adsorption rate indicate that the pressure in this tube was of the order of 10^{-12} mm of Hg.

Since the pattern was so stable, sufficient time was available to measure the light output of the phosphor along the various crystallographic directions as the applied voltage was varied. Light from a certain portion of the pattern was focused on a photometer employing a 931-A photomultiplier tube. These data, which give relative field-emission currents for the various directions, are now being analyzed according to the field-emission equation derived by Fowler and Nordheim. For all practical purposes this equation can be written in the form

$$J = C_1 F^2 e^{-\frac{C_2 \phi^{3/2}}{F}}$$

where J = current density, F = electric field, ϕ = work function, and C_1 and C_2 are constants. Thus, if log J/F^2 were plotted against $(1/F)$, a straight line would be expected which had a slope dependent on the work function. Data concerning the actual electric field at the point have not yet been obtained. Electron microscope shadowgraphs of the point will soon be taken, and it is hoped that definite information of the field can be obtained after the shape of the point is known.

Since the field-emission current depends almost entirely on the potential of the phosphor rather than the voltage applied to the anode, it was necessary to measure the actual phosphor potential. This was accomplished by means of a Compton quadrant electrometer connected as shown in the schematic diagram of Fig. I-1. A spot of aquadag

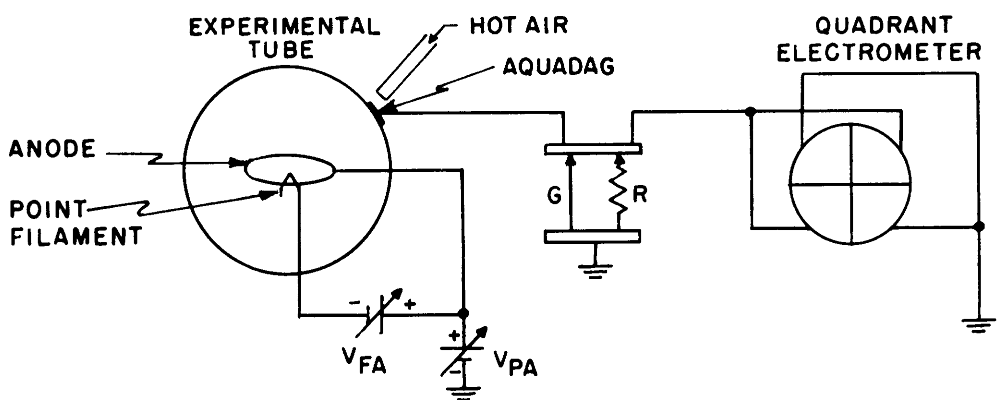

Fig. I-1 Circuit for measuring phosphor potential.

was painted on the outside of the glass envelope at the position where the potential of the phosphor was to be measured. A stream of hot air was directed at this spot of aquadag and the heat controlled so that the glass under the aquadag was brought to a temperature of about 100°C. Such a temperature caused the glass to be sufficiently conducting for the measurements required. A high voltage, V_{FA}, was applied between the filament and anode. This caused the phosphor to assume a potential negative with respect to ground, and with resistor R connected, a deflection was produced on the electrometer. The voltage V_{PA} was then increased until there was no deflection on the electrometer. At this setting, V_{PA} represented the potential difference between the phosphor and anode for this particular value of V_{FA}.

Results taken for several spots of the field-emission pattern indicated that there was no difference in potential over the phosphor in the region bombarded by primary electrons. However, the difference in potential between anode and phosphor was found to be much higher than expected. The following table gives values of the actual phosphor potential as a function of the anode potential. (These data consider the filament at ground potential.)

Anode Potential (volts)	4300	4600	4900	5200	5500	5800
Phosphor Potential (volts)	3263	3372	3467	3555	3636	3709

Furthermore, these data give the phosphor potential only for that region where the field-emission pattern occurred. Throughout most of the range covered, the part of the phosphor outside the field-emission pattern was found to have a potential several hundred volts higher than the data listed in the table. Such a situation might be expected if there were no field-emission electrons striking this region. Then, secondary electrons emitted from that part of the phosphor within the field-emission pattern would be attracted to the other regions of the phosphor where tertiary electrons would be produced. The potential of this region would then be determined by its secondary-electron-emission properties and the collection efficiency of the anode structure for the tertiary electrons. The difference in potential between the two regions of the phosphor would have to be greater than the first cross-over potential of the phosphor. Otherwise, the potential of the region outside the pattern would reduce to that of the region within the pattern. The latter was found to be true for anode potentials about 4300 volts.

A new experimental tube is being constructed. In this tube there will be a layer of "conducting glass" on the inside of the glass envelope, and the phosphor will be deposited on this layer. This design will eliminate the anode structure, and the high voltage can be applied directly to the spherical surface.

M. K. Wilkinson

5. Photoelectric Emission

Construction on the experimental tube for measuring the photoelectric emission from germanium films deposited on a molybdenum substratum has been completed The germanium will be evaporated onto the spherical cathodes from a quartz furnace which is heated by the electron bombardment of a tantalum cylinder placed around the outside of the furnace. The germanium atoms are emitted from a small hole in the furnace and directed through a 2-inch long and 0.3-inch diameter quartz cylinder whose walls are cooler than the furnace. This cylinder defines the beam of atoms and keeps germanium from being evaporated over the whole tube. The cooler walls keep reflection of the atoms to a minimum. With this arrangement the number of atoms per steradian is known and thus the atoms per square centimeter deposited on the cathode at the end of the cylinder is known. The dimensions of the spherical cathode and furnace are such that the distribution of atoms over the cathode is very nearly uniform.

A Perkin-Elmer ultraviolet monochromator will be used in conjunction with this work. It is the monochromator section of the Perkin-Elmer infrared spectrophotometer which has been adapted for the ultraviolet with crystal quartz optics.

Sources of ultraviolet radiation to be used are cadmium, mercury, and tellurium arc discharge tubes. The spectrum from 2000Å to 2600Å is covered by the line emissions of these elements. Intense lines occur at approximately 2001Å, 2142Å, and 2385Å for tellurium, 2288Å for cadmium, and 2536Å for mercury. Other lines of lower intensity occur and may be used to fill in the gaps between the lines listed above. At 400°C for tellurium and 325°C for cadmium the vapor pressure is approximately 0.1 mm of Hg. It is thus seen that a discharge tube of these elements is conceivable.

Since the photoelectric emission is to be measured in electrons per quantum, a standard light source and a vacuum radiation thermocouple will be needed for a calibration of the ultraviolet sources. A bismuth alloy (0.95 bismuth - 0.05 tin) compensated-single-junction thermocouple has been constructed. The thermoelectric wires were made by the Taylor process of sucking the molten metal into a glass capillary tube, heating the capillary over a flame, and drawing out the capillary into a thin fiber. The glass is etched from the wires, and those wires whose resistance is higher than 30 ohms per centimeter are selected for the thermocouple. The receivers are gold foil with gold black deposited on the foil.

The standard source is a tungsten-ribbon-filament lamp set behind a double slit arrangement. With this arrangement the light from the second slit comes only from the ribbon (reflections from the glass envelope of the lamp are eliminated). Also, since the second slit confines the light output to the central part of the umbra of the first slit, it can be assumed that the first slit is a tungsten radiator following Lambert's law. Thus, with the distance between slits large in comparison to their dimensions, simplified equations may be used which will be approximately correct. Since the glass envelope has a wavelength cutoff around 3μ and its exact transmission characteristics in this range are unsure, a 2-cm thick water light-filter will be used to cutoff above 1.4μ. Knowing the transmission characteristics of the water, the emissivity of the tungsten, and the temperature of the tungsten ribbon, the energy from the slits may be calculated. It is found that 0.040 watts per steradian are emitted from the source plus the filter if the ribbon is at 2000°K.

The adjustment of the ribbon temperature to various other values provides the means for the calibration of the thermocouple. It will be assumed that the thermocouple response is independent of wavelength and the calibration may therefore be applied for the measurement of radiation in the extreme ultraviolet. H. S. Jarrett

6. Effect of Impurity Surface States on the Photoelectric Threshold in Semiconductors

Construction of the experimental tube, described in detail in the Quarterly Progress Report, April 15, 1950, is nearing completion. Two sets of Helmholtz coils will surround the completed tube and will serve to balance out the magnetic field of the earth. By using two sets of coils (one set oriented vertically, the other horizontally), there will be no necessity for rotation of the coils about a horizontal axis – a condition that makes for greater compactness because of the size of the coils. A Compton electrometer will be used to measure the photoelectric current in the experimental tube. All of this equipment will be contained in a large copper box for shielding purposes.

As a source of ultraviolet light the 2288 Å cadmium line has been tentatively chosen. A cadmium-vapor discharge tube has been designed and built but not yet tested. It will be run in an oven at about 320°C with the molten cadmium serving as the cathode of the tube. Considerable difficulty has been encountered in obtaining suitably pure cadmium, but it is hoped that this difficulty has now been overcome. A Perkin-Elmer monochromator has been received and will be used in conjunction with the source to isolate the desired spectral line. R. H. Parmenter

B. STUDIES WITH GASEOUS DISCHARGE

Investigation of Low-Pressure Mercury Arcs

Probe measurements have been made in the plasma of a low-pressure mercury arc, and the electron-energy distributions were found to be Maxwellian over a considerable range in energy. However, depletions from a Maxwellian distribution were found in the high-energy region. These depletions have been observed by previous investigators, but limited accuracy of their probe data has prevented a reasonable interpretation of such depletions. As a result of carefully conducted experiments in the present research, probe data have been obtained with sufficient accuracy to allow a good correlation between experiment and theory in regard to depletions of electrons from a Maxwellian distribution. Radial density and potential variations in the plasma have also been investigated; experimental results show good agreement with ambi-polar diffusion theory.

Experimental Procedure. Three mercury arc tubes of cylindrical geometry were used for these investigations. Two of the tubes had a right-angle bend in the main envelope; the third was straight. Various probe arrangements were incorporated into the three tubes. A plane-probe whose axis could be rotated either parallel to or perpendicular to the tube axis was used to investigate distortions in probe characteristics due to drift currents. A telescope-shaped probe array, consisting of five coaxial cylinders extending from tube axis to tube wall, was employed to study radial variations in plasma potential and density. Positive-ion current to the tube wall was investigated with a plane probe mounted flush with the wall; these measurements allowed a determination of the rate of ionization in the plasma.

Very rigorous processing schedules were carried out in the preparation of the experimental tubes in order to minimize the presence of any contaminating gas. The mercury-arc tubes were completely submerged in a constant-temperature water bath, and probes were flashed red-hot to drive off adsorbed mercury immediately before each probe-current reading.

Drift-Current Effects. Measurements were taken at bath temperatures of 22°C, 30°C, 40°C, and 61.5°C, thus covering a pressure range from 1.7 to 35μ. The probe characteristics at all of these pressures showed a depletion of high-energy electrons from a Maxwellian distribution. Measurements with the swivel probe at the lower pressures indicated that drift-current effects caused considerable distortion in the characteristic of probes with surfaces normal to the drift current. However, the distortion was limited to the slope of the probe-characteristic curve; plasma potential and saturation current of electrons were not appreciably affected by the drift current. This means that good determinations of radial potential and density variations can be made with the telescope probes, while the plane probes, when oriented so that they collect only random current, should give the best data for electron-energy distributions. At the highest pressure (35μ) drift-current effects were almost negligible.

Coupling Effects between Probes. Coupling effects between adjacent probes were investigated and found to be quite small. This indicates that the presence of a probe in the plasma does not seriously alter the plasma potential. The small coupling observed was in the proper direction to agree with the Langmuir-Tonks theory, which states that the presence of the probe in the plasma causes a small lowering of plasma potential in the vicinity of the probe; the resulting potential well for positive ions accounts for the observed positive current to the probe, which was too large to be the result of a random current of positive ions.

Radial Potential and Density Distributions. Ambi-polar diffusion theory showed good agreement with the observed radial distributions of density at 30°C and 40°C bath temperature when a cumulative, two-step ionization process was assumed. When a rough correction was made to account for plasma density depletions due to finite probe areas, results at 61.5°C also showed agreement with the diffusion theory when cumulative ionization was assumed. At 22.5°C the experiment showed better agreement with ambipolar diffusion based on a direct, one-step ionization. At this lowest pressure, however, mean-free paths were of the order of tube radius; hence the application of diffusion theory is of doubtful value in determining the ionization process.

Direct calculation of the ionization rate at 22°C from the electron-energy distribution and the known ionization probability indicated that about one-fourth of the observed ionization is direct; the remaining three-fourths is presumably cumulative. At higher bath temperatures the calculated fraction of direct ionization was much smaller, indicating that cumulative ionization predominates. This is in agreement with the results of the diffusion theory discussed in the previous paragraph.

Non-Maxwellian Distributions. Depletions of high-energy electrons from a Maxwellian distribution is believed to be the result of inelastic collisions of electrons with mercury atoms and with the tube walls. A rather close correlation between wall potential and the potential at which depletion sets in was observed over the entire range of arc pressures studied.

Because wall potentials also lie in the range of excitation and ionization potentials, it is impossible to separate the two effects. In any case there must be a net flow of electrons through velocity space from low energies to high energies, where they suffer inelastic collisions and drop back again to low energies. Probe curves have been calculated from the theoretical distribution necessary to cause this flow; these calculated probe curves show excellent agreement with the experimental probe curves at all pressures studied except the lowest (22°C bath temperature). At this lowest pressure the mean-free paths are the order of tube radius; the theory is therefore not expected to give good agreement.

Correlation between observed distributions and theoretical distributions shows promise of yielding additional information, including a calculation of the electron-electron interaction.

R. M. Howe

C. NEW EXPERIMENTS

A new mercury-arc tube is being constructed. The geometry of the tube will allow studies of the arc plasma over a much wider range of tube currents than possible with the previous tubes. A plane probe movable from tube axis to tube wall will be incorporated to continue the investigation of radial potential and density variations in the plasma. Two probes separated by a considerable distance along the tube will allow an accurate determination of longitudinal electric field. Drift current effects from both cathode and anode directions will be compared with random current by means of a multisection probe at the tube axis. In addition, a wall probe will be used to measure ionization rates in the plasma.

It is hoped that probe measurements in this new tube will further add to the information obtained from the previous three mercury-arc tubes.

R. M. Howe