

# I. PHYSICAL ELECTRONICS

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## RESEARCH OBJECTIVES

Present research projects related to the physics of thermionic conversion may be summarized as follows.

### 1. Ionization Probability of Cesium

Atoms in the gaseous phase may be ionized by electron bombardment if the electron energy exceeds the ionization potential. For cesium this ionization potential is 3.89 volts. The ionization probability of mercury as a function of electron energy in excess of its ionization potential has been established quantitatively. There are no comparable data applicable to cesium and other metallic vapors, which would be especially useful in connection with thermionic conversion which would include the other alkali metals. It is, therefore, very desirable to obtain this information, since it plays an important part in the understanding of plasma formation and maintenance in the cesium type of thermionic converter.

A technique for the measurement of the ionization yield is being developed which depends on a "crossed-beam" method. A collimated atomic beam is made to pass at right angles to two electron beams. The interpretation of the data related to the ion production in these two beams permits a determination of the strength of the atom beam. The ion production as a function of the electron energy will be measured after the ions have been separated by means of a quadrupole mass spectrometer. The final ion-detection device involves the actual counting of ions that arrive at the surface of an electron multiplier. Electrons generated under ion bombardment are then accelerated through the multiplier and detected at the output by means of a pulse counter. It is anticipated that not only will it be possible to determine the ionization probability of cesium with this device but also to carry on further researches to determine the ionization probability of other metal vapors that can be evaporated from a source and formed into a collimated atomic beam. A modification of the method described above is to be used, first, for cesium study.

### 2. Work-Function Determination by the Electron Energy Distribution Method

The maintenance of the collector work-function at a low and controllable value is of prime importance in the design and operation of an efficient thermionic converter. It is not enough to say that the collector work-function should be the absolute minimum attainable because, for particular surface conditions, this minimum might occur only at a relatively high temperature which, in turn, would indicate an excessive thermionic emission from the collector. It is important, therefore, to devise a scheme for determining the collector work-function for selected surfaces, especially single-crystal surfaces, in the presence of cesium.

The experimental method that is being used here involves the production of electron emission from a ribbon filament source. Parallel to this source there will be three conducting surfaces with a single small circular opening in each one, so lined up that electrons collimated by means of a magnetic field will be able to pass through all three of these apertures. This collimated beam of electrons will then impinge on the collector, which is similar in construction to the emitter. The part of the surface that receives the beam will be a single crystal with a selected crystallographic orientation. In order to determine the work-function of the collector by this means, it is necessary to study the current-voltage characteristic in the retarding range to determine the characteristic temperature that describes the electron-energy distribution. This temperature must be the same as that of the emitter for the experiment to be correctly interpreted. If

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this test proves satisfactory, the work-function of the collector can be determined directly from the knowledge of the current density and the applied voltage. In order to make this study in the temperature range for which an appreciable electron emission from the collector can take place, the center diaphragm of the three described above can be modulated by the application of a square-wave, cutoff potential, and a sharply tuned amplifier can detect the modulated current in the presence of a considerable background of direct current.

### 3. Determination of the Collector Work-Function in a Thermionic Diode Structure

The control and the evaluation of the collector work-function is an important aspect of any thermionic converter structure. This work-function depends on the material, its crystallographic orientation in case it is a single crystal, its temperature, and the cesium atom arrival and evaporation rates. It is advantageous to have the work-function as low as possible, consistent with a sufficiently low collector temperature, so that thermionic emission from this electrode is not objectionable under normal operating conditions. A new method for evaluating this work-function is being investigated.

A plane parallel diode is operated at a sufficiently high cesium pressure so that the electron emission from the normal emitter will be space-charge limited. Some ions will be produced at the emitter and these can be swept across the diode with a very small ion accelerating field. The suppression of the arrival of electrons by the negative applied potential at the collector results in the formation of a positive ion sheath in the immediate neighborhood of the collector. If the collector is cold, its electron emission can be reduced to a value appreciably less than the ion arrival rate, which measures the constant rate of production of ions at the emitter surface. As the temperature of the collector is increased, the total measured current, at a constant applied voltage of approximately -4 volts, will increase, and, by subtracting the ion background current from the measured current, electron emission can be evaluated. Continued raising of the temperature of the collector will result in electron emission from the collector into the space with a current that is as much as 100 times the background current. It is important in this method of operation that the electrons thus emitted be accelerated as little as possible because if ion generation takes place as a result of electron bombardment, this new ion arrival rate will be confused with electron emission. A detailed analysis of the current-voltage curve, beginning at the open-circuit voltage and carrying it to more negative values, permits the observer to evaluate the reliability of the results. If the electron emission current density in  $\text{a/cm}^2$  at a given temperature  $T_2$  is denoted by the symbol  $I_{\text{ob}}$ , then the effective work-function of the collector is given by

$$\phi_{\text{eff}} = 2.3 \frac{kT_2}{q} (2.08 + 2 \log_{10} T_2 - \log_{10} I_{\text{ob}}).$$

The value of  $\phi_{\text{eff}}$  at various collector temperatures and cesium arrival rates can be determined.

### 4. Cesium Plasma Properties as Determined by Langmuir-Probe Analysis

A conducting surface placed in a cesium plasma maintained between an emitter and a collector can be used to gather information relative to the carrier density in the plasma and can determine the plasma potential near the inserted electrode. Efficient high-density thermionic converters operating by the plasma mode of conduction have positive ion sheaths both at the emitter and at the collector. It is important to have independent means to determine the voltage drop over these sheaths. The theoretical analysis indicates that there are indirect methods for determining this plasma potential. It is, therefore, desirable to make an independent measurement of plasma potential and carrier density; if it is found to be in agreement with the indirect methods of determination it will establish more confidence in the proposed theories of interpretation. A

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practical diode does not lend itself to the insertion of probes, and therefore it is very important to establish this connection between the direct and the indirect methods of analysis with geometrical configurations that do not conform to efficient operation as a thermionic converter.

The experimental procedure is to build a diode that has a cylindrical emitter and a concentric cylindrical collector. The emitter may be indirectly heated or it may be pulse-heated so that there will be no drop in potential over the surface of the emitter, other than that associated with its inhomogeneity. The probe will be a tungsten wire with its axis parallel to the axis of the diode system and located in the space between the emitter and the collector. This wire may also be heated to establish a particular surface condition. The current-voltage characteristic will be traced out on an oscilloscope and photographed for later detailed analysis. It is anticipated that plasma densities and plasma potentials can be determined as a function of the operating parameters with reasonable accuracy. It may also be possible to determine some facts relative to the work-function of tungsten in the presence of cesium. Since there is already a considerable supply of information in this area, the acquisition of additional data may serve to give confidence to the interpretation of the data that are expected to be acquired in this project.

### 5. Adsorption Properties of Single Crystals of Tungsten before and after Carbonization

Experiments with clean tungsten crystals show that different crystallographic orientations adsorb cesium with specific characteristics. Generally speaking, the (110) direction and the (112) direction hold cesium best. This is indicated by the fact that at a given cesium pressure these originally high work-function surfaces become the lowest of all. Experience in the field of thermionic emission from thoriated tungsten has led to the commercialized technique of carbonizing the surface layer. After carbonization, this layer holds thorium better than it did before. The purpose of this experiment is to find out whether or not surface treatment of tungsten can create a situation in which cesium will hold on to give a suitably low work-function at a very high temperature and not also require an excessive arrival rate of cesium.

Selected tungsten wire can be polished and processed in such a manner as to make long single crystals grow in the wire. These single crystals exhibit all of the available crystal directions that combine as  $(11x)$ , with  $x$  taking on values from zero to infinity. The electron emission is seen on a concentric, fluorescent screen. After the crystal is grown and its orientation determined, it can be carbonized. Cesium is then admitted and the emission pattern reinvestigated to see to what extent the carbonization has influenced the absorption properties of the single crystal.

### 6. An Emitter Work-Function Measured by Its Ion Production Rate

Plasma converters operated at relatively high cesium pressure and relatively low emitter temperature can operate even though the thermal production of ions at the heated surface is insufficient to maintain the plasma. Operation of this type depends on an initiation of the plasma mode of operation, which develops an injection sheath at the surface of the emitter. After this sheath is developed, it is possible to maintain the plasma mode. It is difficult to obtain information concerning the work-function of the emitter under these conditions and it is considered worth while to try to find an independent method of estimating it. Before the plasma mode is developed, the electron emission is limited by its own space charge, and a very weak plasma may develop because the electron space-charge sheath can accelerate those ions that are produced thermally into the intervening space. Under these circumstances, the application of a very moderate, ion accelerating potential to the collector can sweep the ions out as fast as they come in. Ion production depends on the rate of arrival of cesium atoms at the hot surface and the probability that a cesium atom will leave the surface as an ion. This probability is work-function-dependent.

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A diode designed as a plane parallel structure may be operated in this manner and a study can be made of the ion production at the emitter surface as a function of the atom arrival rate and the emitter temperature. The dominant factor in determining the ion production is related to the energy difference expressed as  $\exp(V_1 - \phi) / \bar{V}$ . This exponent represents the difference between the ionization potential and the work-function computed in units of the voltage equivalent of the surface temperature which is  $\bar{V}$ . This method of estimating the true work-function of the emitter under conditions inappropriate for its determination as an electron emitter is an entirely new approach, and will be studied to see how well it can answer the important question as to the true work-function to be expected under these conditions. Ultimately, a correlation can be set up between the work-function, determined in this manner, and the diode current that is observable after the plasma mode of operation has been generated.

### 7. Ionization by Electrons and Light at a Collector Surface

Many voltage-current curves on plane parallel cesium plasma diodes seem to be extremely complex; this complexity is determined by the controllable parameters which include the emitter material, the emitter temperature, the collector material, its temperature, the spacing, and the cesium concentration. Under moderately high pressure conditions, the emitter work-function is so low that an insufficient number of ions are present to permit the free flow of electrons across the space. Analysis seems to indicate that when the electron bombardment energy at the surface of the collector approaches a value of approximately 2 volts, a new supply of ions seems to emerge. Energetically, it would be possible to produce ions by a cumulative process. It might be possible to produce ions by the electron bombardment of atoms that are momentarily in the process of evaporation from the collector, and still near enough to the collector to be in the polarizing field that exists there. The question is, Can ions be produced by low-energy electrons, and furthermore, is it possible that the absorption of radiation at the surface produces ions?

The tube design involves the use of three indirectly heated tantalum cylinders located as though they were at three corners of an equilateral triangle. Not far outside this triangle is a fine-wire ion collector. The entire assembly is enclosed in suitably designed shields so that no ions can reach the fine-wire collector that do not originate within the shielded system. The ion collector will be connected to a power supply and biased 50, or more, volts negative with respect to the rest of the system. With no other voltages applied to the elements except those needed for the indirectly heated tantalum cylinders, their temperature can be brought up to a suitable operating value. A very few ions might be produced thermally and light from the surfaces can produce photoelectrons. These currents can be measured as a background. Biases will be applied so that one of the tantalum cylinders coated with cesium will become a low-temperature electron emitter and can bombard the other two. If this bombardment produces ions with an electron energy less than 3.89 volts, then the effect that we seek will be established. If no ions are produced at low voltage, then the production of ions in an actual diode will have to be explained by some other mechanism. A window is provided so that ionization by light can also be investigated.

### 8. Thermionics – Energy-Conversion Electronics

The interpretation of the electrical properties of thermionic-conversion diodes demands a synthesis of knowledge of widely different aspects of physical electronics. Emission properties of surfaces for ions and electrons depend not only on the materials and their temperatures but also on the arrival rate of atoms such as cesium. Properties of the collector also depend on these factors, and the conducting medium depends on the availability of suitable carriers, which may be electrons, ions, or both. Converter performance depends not only on the understanding of the physics related to these components, but also on the ready availability of numerical calculation methods that can

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become quite tedious if a vast number of calculations has to be made.

A book is being prepared with the aim of making available to its readers all of the necessary tools for plasma-diode analysis and a moderately complete theoretical treatment is included to indicate how these "tools" were developed. Unfortunately, some of the basic facts are not known as quantitatively as would be desired, and therefore the treatment is made as simple as possible, since some of the most essential numbers have had to be guessed at. Chapters in the latter part of this book are devoted to the actual analysis of experimental curves and data to show examples of the use of all aspects of the theoretical treatment that is presented. It is hoped that this book will be available within six months. It will be published by Reinhold Publishing Corporation and will also be Special Technical Report No. 4 of the Research Laboratory of Electronics.

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