REVIEW OF THE PHYSICS OF THERMIONICS 1960

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REVIEW OF THE PHYSICS OF THERMIONICS

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Abstract

Heat may be converted directly to electrical power by means of either the vacuum or the plasma thermionic diode. The latter holds the greater promise of being valuable for space-power applications. The input heat is delivered to the emitting surface and the excess heat is radiated from the cooler electron collecting surface. The efficiency of a device depends on the use of a low work-function collector and a minimum of unwanted heat losses. The best gas for the plasma seems to be cesium which serves to eliminate space charge and conduct the electric current across the diode. Some of the basic concepts related to the plasma diode are presented.

Introduction

The physics in terms of which the various space-power systems can be understood varies so radically from system to system that a brief review of the most important facts related to thermionics is in order. The two most important thermionic converters of heat to electricity are the vacuum and the plasma diodes. In both of these devices electrons are emitted from the heated surface and are collected at a nearby surface of distinctly lower temperature. Although some applications may be found for the vacuum diode, efficiency cannot be attained with an interelectrode spacing greater than 10 to 20 microns. It is mainly for this reason that a large fraction of the present research effort is being devoted to the development of the plasma diode as a device which holds considerable promise as a generator of electric power from heat for space-power applications.

Plasma Properties

An ionized gas is an excellent conductor of electricity when the space concentration of electrons is exactly equalized by a corresponding concentration of positive ions; thus a low-pressure arc such as that found in a fluorescent lamp conducts electricity from one electrode to the other by three different mechanisms. The heated filament at one end injects electrons through the emitter sheath into the plasma region. In the fluorescent lamp this sheath occupies a very small fraction of the total length of the lamp. A small gradient in potential causes the electrons within the plasma to acquire a small drift velocity superimposed upon the random motion of the electrons within the plasma. Thus the plasma conductivity is dominated by the product of the electron concentration and the drift velocity. Since the electron concentration is not necessarily uniform across the entire cross-section of the conducting plasma, the total current observed in the external circuit is obtained by the integration of the local drift current density that crosses any imaginary boundary plane through which all of the conduction current passes.

Near the electron-collecting electrode is the collector sheath. This is a region in which the space charge may be predominantly positive or it may even be negative or zero. The determining factor is the relation between the total drift current demanded at this electrode and the integrated random current. The meaning of the term "random current" is best illustrated by the statement that it is equal to the product of one-half the electron density multiplied by the average velocity with which the electrons cross an imaginary boundary within the plasma region. Since this average velocity is very often much greater than the average drift velocity a positive ion space-charge sheath is likely to form at the electron collector if the area of the collector is large. The thickness of a collector sheath is comparable with that of the emitter sheath and therefore constitutes an extremely small fraction of the total conduction path in a fluorescent lamp.

The plasma region in an ionized-gas conductor is practically free from space charge because of the equality of density of electrons and positive ions. Electric fields are generally very weak and conduction to external circuits is maintained by a very small drift velocity of the electrons superimposed on a very high speed random motion. One difference between the plasma diode and the usual low-pressure arc is that the diode plasma is likely to extend over only a few mean-free path-lengths of the electrons instead of its extending over thousands. As a consequence, completely different ionizatinn mechanisms must be invoked for the two cases. In the fluorescent lamp, electrons maintain their high random motion because they receive energy from the externally applied electric field. In the plasma diode, electron energy is acquired as electrons are injected from the heated emitting surface through the positive ion space-charge region that constitutes the emitter sheath.

The ionization mechanism in a particular plasma diode depends on the pressure and the nature of the gas and whether or not some totally extraneous mechanism is available to create the ionization. The cesium diode is considered to be very promising for space-power applications and most designs depend on a sufficiently copious ionization at the hot emitter surface not only to neutralize space charge but to create a positive ion sheath for electron injection into the plasma region. Thus the emitter temperature and the emitter work-function as well as the cesium pressure are very important parameters of the problem.

Emitter Work-Function

Detailed knowledge concerning the "true" work-function of a particular surface is of primary importance in the understanding of both the electron emission capability of an emitter and the ionization capability of the same surface. The definition of the "true" work-function is the energy difference between an electron at the Fermi level in the interior of the emitter compared with the potential energy of an electron at a distance of approximately 10^{-6} cm from the emitter surface through which the electron has passed to find itself outside of the metal. Most work-functions that are quoted in the literature are determined from a Richardson equation analysis of the average thermionic emission from a specified material. This is a poor method for the determination of the true work-function. For example, numerous references indicate the Richardson work-function of tungsten to be 4.52 electron volts, whereas actually the true work-function of tungsten varies between approximately 4.3 and 5.4 electron volts, depending on the particular crystallographic orientation that defines the surface through which the electron escapes. This wide variability in the work-function of a particular material is of great importance in a cesium diode that might use a tungsten surface as the emitter. At high temperatures the high work-function area, namely the (110) surface, is the most efficient ionizer of cesium. At moderately low temperatures the same surface is the one which holds cesium most tenaciously and becomes the lowest work-function area because of the adsorption of cesium and the creation of a dipole moment per unit area favorable to the reduction in the work-function. As the result of this reduction in work-function, the electron emission density from the area defined by this particular direction shifts over from the area of minimum emission density to become the area of maximum electron emission density. These statements are made in order to emphasize the importance of promoting research that will enlighten us all with regard to the basic physics of electron emission and ion production.

Adsorption and Ionization of Cesium at High Temperature Surfaces

A research study, the results of which were published by Taylor and Langmuir(1), serves as the most suggestive source of information concerning the adsorption properties of tungsten for cesium and the consequent influences on the electron emission capability, the ionization capability and the evaporation rate evaluation. Taylor and Langmuir deduced that the heat of vaporization of cesium from a hot tungsten surface is expressible in electron volts as 2.83. They also concluded that the energy required to evaporate an atom from the liquid state to the gaseous state is 0,773 electron volts. Thus, if other factors are practically the same, then the arrival rate of cesium atoms at a tungsten surface will exactly equal the evaporation rate if the temperature of the tungsten surface is 3.65 times greater than the liquid cesium temperature which is establishing the cesium arrival rate in the experiment. As a consequence of this relation there is practically no adsorption of cesium on tungsten if the tungsten temperature is appreciably above 3.6 times the cesium temperature and since the work-function of tungsten on all of its known surfaces is higher than the cesium ionization potential by approximately 0.4 electron volts, practically every cesium atom that strikes the tungsten surface of this temperature evaporates as a cesium ion. If the tungsten temperature is lower than 3.6 times the cesium temperature, then adsorption of cesium takes place, the ion production rate falls rapidly by a factor of 10 or more and the electron emission capability increases tremendously.

It is again to be emphasized that in practical diodes most likely to be used in space-power applications, facts such as these play a very important although perhaps obscure part in the control of the performance of the specific diode configuration.

Motive Diagrams

Fundamental to the understanding of diode performance is the concept put forward by Langmuir years ago of the

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"motive" diagram. As an electron traverses from the interior of the emitter through the surface field that holds electrons to metals, the dominant mirror-image forces are the most important at distances less than 10^{-6} cm. Emitter space-charge fields become important just before the electron enters the plasma and are also generally found near the collector. Finally the strong mirror-image field draws the electron into the collector. The potential energy of the electron changes from place to place depending on all of the forces that act upon it. The motive diagram is a graphical representation of the potential energy of an electron as it traverses the path described. Four typical motive diagrams are shown in Figs. 1 through 4.

A brief description of these diagrams follows. Figure 1 shows the Fermi level of the emitter as FL and the emitter work-function as ϕ_1. A surface potential is thus established at s_1 with respect to the emitter Fermi level. In the space between the emitter and the collector in a high-vacuum diode, electrons create a space-charge minimum. This is shown to extend down to ϕ_m with respect to the emitter Fermi level. The surface potential of the collector is ϕ_2, more negative than the collector Fermi level with ϕ_2 the collector work-function. Any externally applied or measured voltage between the emitter and the collector is directly related to the displacement of their Fermi levels as shown by the arrow V. The introduction of a small pressure of cesium can, if it is ionized at the hot surface, result in the elimination of the electron space-charge sheath as shown in Fig. 2, whereas the introduction of a still higher pressure of cesium can result in the creation of a positive ion space-charge sheath of thickness S_1, which will inject electrons into the plasma space with an energy of V_p. The collector sheath is shown here also as a positive ion sheath of thickness S_2. The final motive diagram shows a condition of open circuit in which it is noticed that the assumed motive diagram changes most in the collector space and very little in the plasma space or the emitter sheath.

Concluding Remarks

The cesium plasma diode, in comparison with vacuum diode, cannot be understood in terms of basic physics in as much detail as would be desired because of the lack of fundamental data not yet available from the research laboratory. A few general remarks can be made. (1) Operational conditions, which yield a very low collector work-function, are favorable to improved efficiency. (2) Consistent with this requirement, the diode spacing should be a relatively few mean-free paths of electrons in the cesium gas present between the electrodes. (3) A high work-function emitter, operating at a relatively high temperature, can develop a sufficient emitter sheath to inject electrons into the plasma with considerable energy. These high-energy electrons are randomized in their motion by plasma oscillations to give them an energy distribution characterized by a temperature as high as 5000°K. The ionization rate can then equal the ion loss rate and good conductivity can be maintained. Low work-function emitter materials may very well deliver a very much larger number of electrons and yet produce an insufficient number of ions to create an important emitter sheath. If the ion density is sufficiently high to neutralize electron space charge, the performance of this diode may very well be superior to the performance of the higher work-function diode. Until further research is done, it will be difficult to state with confidence the diode configuration most likely to be used for space-power applications.

Reference

1. J. D. Taylor and I. Langmuir, Phys. Rev. 44, 432 (1933).

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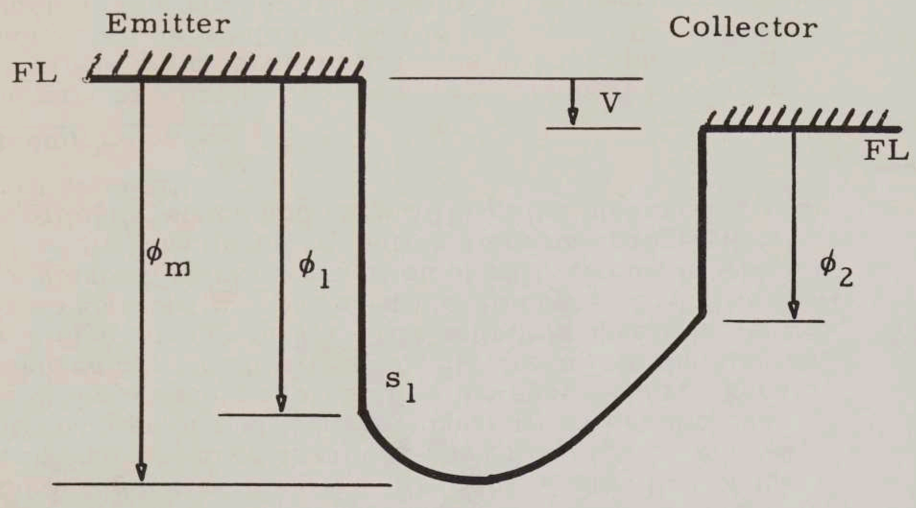
1

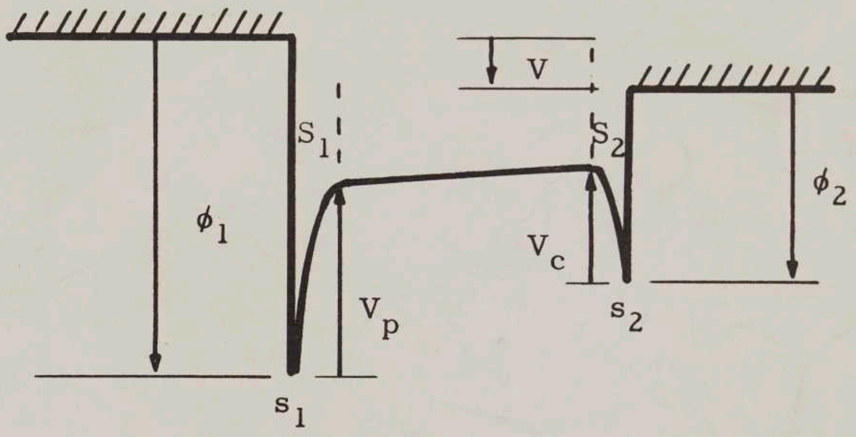
MOTIVE DIAGRAMS FOR DIODE

3

HIGH VACUUM DIODE

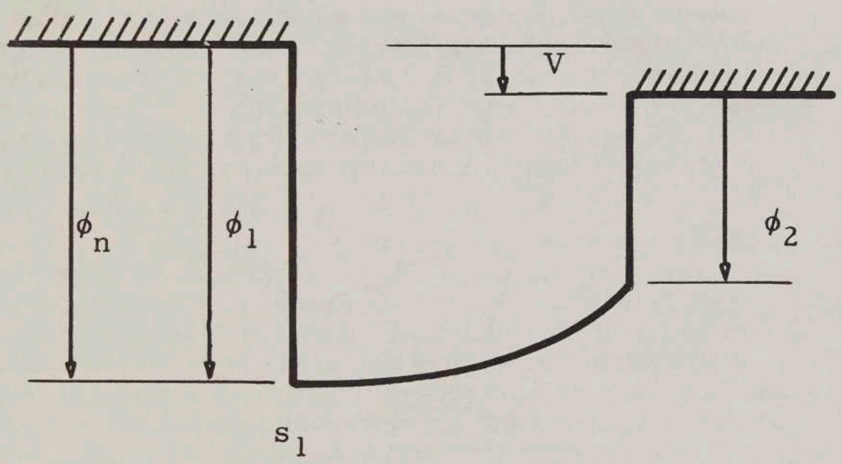


HIGH PRESSURE Cs



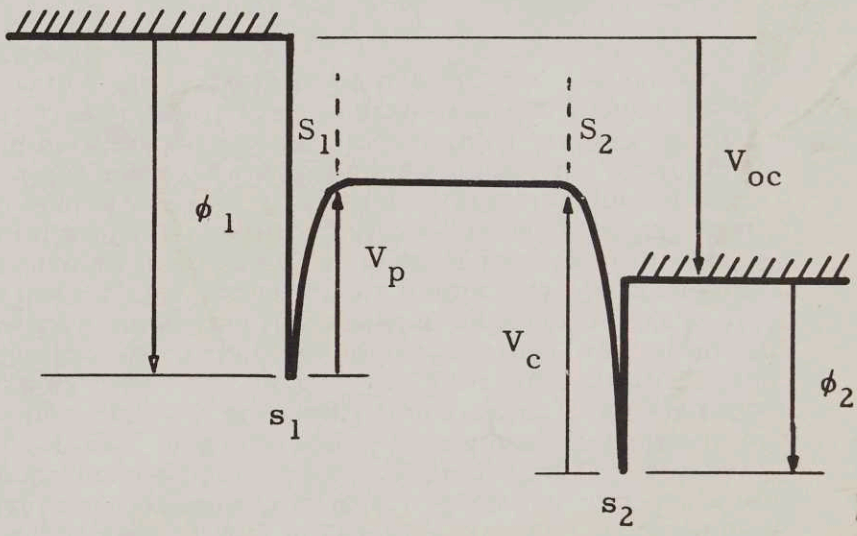
2

MEDIUM PRESSURE Cs



4

HIGH PRESSURE Cs. OPEN CIRCUIT



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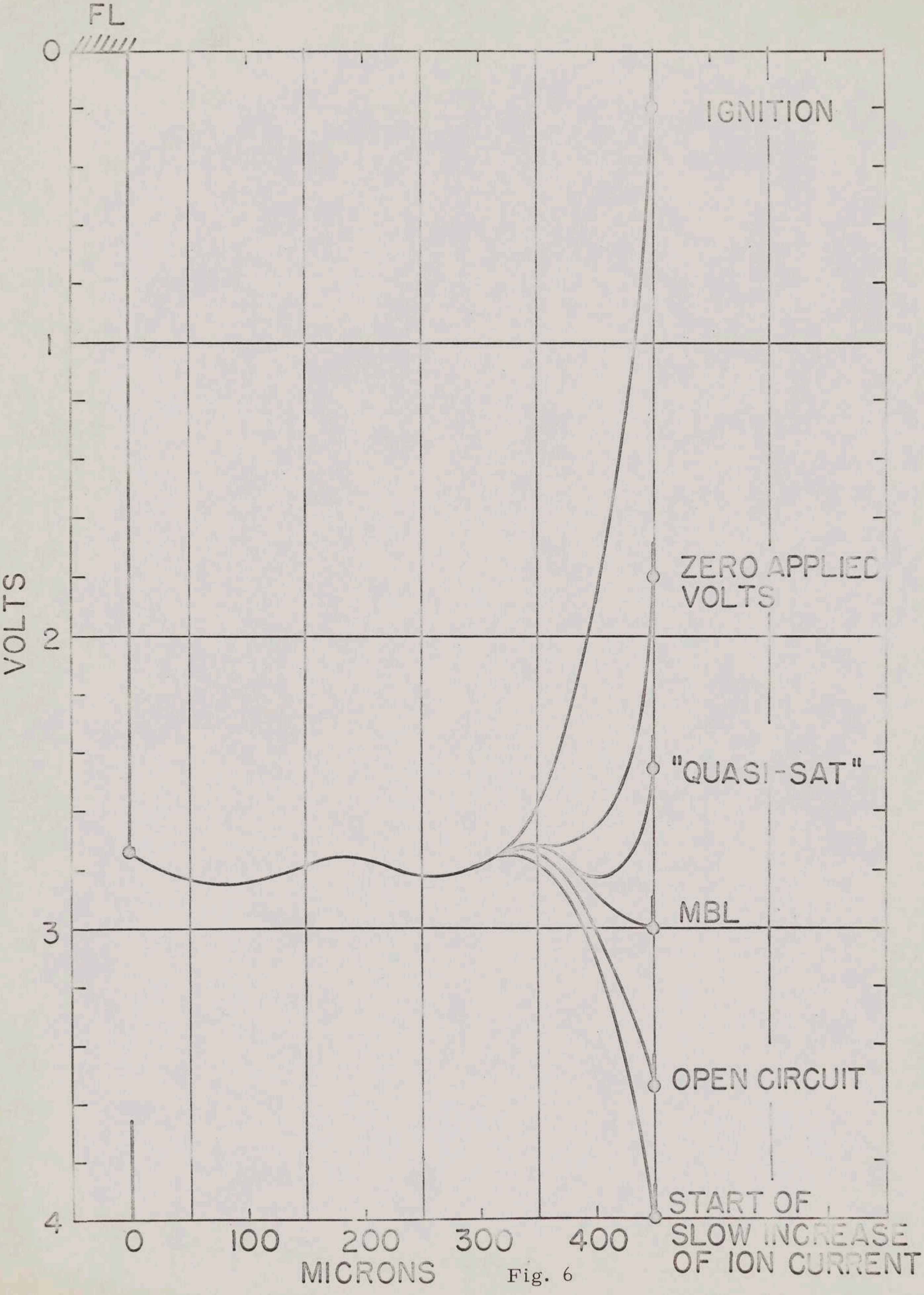
FL
0
1
2
3
4
VOLTS
0
100
200
300
400
MICRONS
IGNITION
ZERO APPLIED VOLTS
"QUASI-SAT"
MBL
OPEN CIRCUIT
START OF SLOW INCREASE OF ION CURRENT

Fig. 6