CAN SOME STANDARDIZATION OF THERMIONIC TERMS AND CONCEPTS BE ACHIEVED NOW? by W. B. Nottingham (undated

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Glossary of Symbols

a	area in Eq. 8
I	current density, Eq. 7
i_{ob}	observed current, Eq. 8
I_{ob}	computed current density (i_{ob}/a), Eq. 9
h	Planck's constant 6.625×10^{-34} joule-sec, Eq. 4
k	Boltzmann's constant 1.38×10^{-23} joule/deg, Eq. 4
m	electron mass 9.11×10^{-31} Kg, Eq. 4
q	electron charge 1.6×10^{-19} coulomb, Eq. 1
T	temperature in Kelvin scale, Eq. 4
V	potential difference, Fig. 4
$\bar{V}$	electron-volt equivalent of temperature, Eq. 6
w	diode spacing, Fig. 3
W_i	Fermi energy level, Fig. 2 and Eq. 15
W_a	Electron affinity, Fig. 2 and Eq. 15
x	distance, Eq. 1
$x_{99.9}$	distance for 99.9 per cent of work-function, Table 1
X_1	distance characteristic of surface, Eq. 1
α	coefficient in Eq. 10
α_R	coefficient in Eq. 11
β	coefficient in Eq. 10
γ	coefficient in Eq. 10
ϵ_o	permitivity of free space, 8.85×10^{-12} farad/m
μ	micron or 10^{-6} m, Table 1
ϕ	true work-function, Eq. 2
ϕ_{eff}	effective work-function, Eq. 8
ϕ_o	true work-function at $T = 0$, Eq. 10
ϕ_R	Richardson work-function

Can Some Standardization of Thermionic Terms and Concepts[Δ] Be Achieved Now?

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INTRODUCTION

Discussions related to the physical electronics of thermionic energy converters invariably stress the important concept of "work-function." It is generally not sufficient to use the term "work-function" without additional defining adjectives which are: "true," "effective," and "Richardson." The three work-functions associated with these three adjectives each have specific usefulness when the terms are clearly understood and used in the limited manner associated with the specific concept. It will be the purpose of this memorandum to state as concisely as possible the present writer's views concerning these points. Following this presentation will be some remarks related to the identification of component parts of the thermionic diode, the drawing of motive diagrams, and the display of current-voltage curves.

WORK-FUNCTION(1)

True Work-Function

The true work-function may be defined in either of two ways that are so nearly equivalent that there is no need to discuss any theoretical difference. One statement is: "The true work-function is the work required to transfer an electron from the interior of a homogeneous conducting material across the material boundary which is infinite in extent and perfectly uniform." This definition is really not such a very good one, looked at operationally, since the electrons within the interior of a conductor in a condition of thermodynamic equilibrium occupy a very wide range of energy states. It might seem that the removal of an electron in a high energy state would require less energy than the removal of an electron from a lower energy state. This is not true because the definition when stated this way implies that after the removal of any electron, other energy transfers are required by the whole system of electrons to return it to its thermodynamic equilibrium state. All energy changes must be included

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in the calculation. The second and far more useful definition is: "The true work-function is the energy difference between the Fermi Level energy in the interior of a conductor and an electron having no appreciable kinetic energy and in a state corresponding to a position which is just outside of the conductor."

Although it is not appropriate to this abbreviated report to try to prove that these two definitions are essentially the same, it is desirable to establish a criterion by which the reader can visualize more specifically the statement "just outside the conductor." It has been possible to examine very homogeneous surfaces and establish the fact that the force that acts on an electron as it leaves any really good conducting surface is the mirror image force beginning within approximately two angstrom units of the last layer of atoms and extending on to distances comparable with the dimensions of the homogeneous surface. This force function is expressed by the following equation:

$$F(x) = -\frac{q}{16\pi (X_1 + x)^2 \epsilon_0} = -\frac{3.6 \times 10^{-10}}{(X_1 + x)^2} \text{ newtons per coulomb (or volts/meter)} \qquad 1$$

The insertion of the required mks units yields a determination of this force expressed in "Newtons per coulomb" or its exact equivalent "volts per meter." Note that if x takes on the value $-X_1$ then the magnitude of the force becomes infinite. This does not occur in nature because no atomic plane is infinitely smooth and infinitely conducting. Thus X_1 may be defined as a constant characteristic of the substance such that the integration of this equation from $x = 0$ to $x = \infty$ will yield a number which is an arbitrary fraction of the actual work-function. Thus if we take this arbitrary fraction to be unity, the range in the value of X_1 is from 3.6×10^{-10} meters (or 3.6 angstrom units) for a 1 volt work-function to 0.72×10^{-10} meters for a 5 volt work-function. This result comes from the integration of Eq. 1 between the limits of 0 and ∞ to obtain

$$\phi = \frac{3.6 \times 10^{-10}}{X_1} \text{ el-volts} \qquad 2$$

This equation rearranged as:

$$X_1 = \frac{3.6 \times 10^{-10}}{\phi} \text{ m} \qquad 3$$

serves to indicate the distance from the mathematical mirror-image plane over which the integration of a mirror image function to infinity yields any arbitrarily chosen work-function ϕ. All of this is introduced in order to demonstrate numerically that as an electron moves away from a surface to a distance 1000 times greater than this characteristic distance X_1, 99.9 per cent of the work required to move an electron on to infinity will have been used. These statements may be summarized by Table 1.

Table 1

Approximate distance beyond which the mirror-image function contributes less than 0.1 per cent of the work required to remove an electron

ϕ in ev	X_1 in m.	$x_{99.9}$
1	3.6×10^{-10}	$0.30\ \mu$
3.6	1.0×10^{-10}	$0.10\ \mu$
5.0	0.72×10^{-10}	$0.072\ \mu$

At a distance close to only 100 X_1, the mirror-image function can contribute less than 1 per cent of the additional work required to remove it to infinity. Since most of the materials of interest in thermionic conversion work are formed of small crystals or even large ones depending on the heat treatment, the crystal faces themselves will generally have dimensions of 1 micron or greater. Since each facet of a crystal characterized by a different surface arrangement of the atoms will have a different true work-function, local electrostatic fields of the "contact potential" variety will often dominate the force function acting on an escaping electron at distances greater than 0.1 micron. Space-charge fields are also important at these greater distances. It is because of the fact that such a large fraction of the integral of the force acting on an escaping electron is associated with the travel through a small fraction of a micron that it is legitimate to define the true work-function of a particular area of a conducting surface as the energy difference between the Fermi level energy within the material and that of an electron at rest just outside of the surface where "just outside" implies a distance from the last atomic layer of the order of 0.1 micron or even slightly less. In terms of this true work-function and the temperature it is justified to maintain that the electron density at that point is given by the formula

$$n_s = \frac{2(2\pi mkT)^{3/2}}{h^3} e^{-\frac{q\phi}{kT}} \qquad 4$$

$$n_s = 4.83 \times 10^{21}\ T^{3/2}\ e^{-\frac{\phi}{V}} \quad \text{electrons/m}^3 \qquad 5$$

where

$$\bar{V} = \frac{kT}{q} \qquad 6$$

The density of electrons just outside the surface that is given by these formulae is the one which is identically equal to that required to give a thermodynamic equilibrium current sometimes mistakenly identified as the "saturation current" of

$$I = 120 \times 10^4\ T^2\ e^{-\frac{\phi}{V}} \qquad \text{amp/m}^2 \qquad 7$$

Note that nothing has been said in this discussion of the true work-function of a surface that implies that it is independent of the temperature. It is a rare circumstance associated with a very few examples of emitter surface structure that the true work-function ϕ is independent of the temperature over a wide range of values. In fact there are no examples for which good experiments have proven that the true work-function is a constant for all values of temperature. It is therefore important in talking about the temperature coefficient of the true work-function to be very specific concerning the range of temperatures involved and how the reference ~~of the~~ to the absolute value of the work-function is defined.

The need for knowledge concerning the true work-function cannot be over-emphasized. A Voltmeter~~s~~ ~~that~~ measures the difference in potential that drives electric current through the output load of a thermionic converter. ~~and~~ Voltmeter readings ~~that~~ may be used to evaluate the open-circuit voltage of a converter. They always give measurements that show the difference in the Fermi Levels at the meter terminals. To understand the physics associated with the electron emission at the emitter, the production of ions or their adsorption at the emitter, ~~and the same at the collector~~, we must demand full information concerning the true work-function of the surface~~s~~ including ~~their~~ its inhomogeneous character. Most of the important dynamic phenomena that determine the operation of a thermionic converter are critically sensitive to true work-function values. These remarks apply to the collector as well as to the emitter.

Unfortunately the true work-function of a surface is very difficult to evaluate. Even a single crystal of tungsten does not have a single true work-function, but depending on the exposed crystallographic structure, the true work-function will cover a range from approximately 4.3 to 5.3 ev or more. The same applies to single crystals of tantalum and molybdenum although specific and accurately known values of their true work-functions are not as well established as those for pure tungsten. ¶ The adsorption on refractory materials of even a small fraction of a monolayer of electro-positive materials such as cesium, thorium, barium, and others lowers the true work-function very significantly. Langmuir(2) estimates that a monolayer of cesium on tungsten contains 4.8×10^{18} atoms per m^2. The interatomic distance then would be 4.6×10^{-10} meters (or 4.6 angstrom units). In the immediate neighborhood of an adsorbed atom, extremely intense "built in" electron-accelerating fields will exist over a distance of a few angstrom units. It is this built-in field that, when averaged over the surface, gives a dipole moment per unit area which is a direct measure of the reduction in the true work-function of the surface as a result of the adsorption of the electro-positive material such as cesium. For coverages of cesium more than approximately 10 or 15 per cent, the average distance between cesium atoms is so small that their effect averages over a particular crystal facet in a manner to reduce the value of the true work-function over the entire face. Local fields between these atoms are superimposed on the mirror-image field. Because of them an increase in emission as a function of the externally applied voltage shows up in measurement as a deviation from the "Schottky line" which would characterize the same geometrical structure if only the mirror image force were acting. Again it has been well established by experiment that as the fraction of the surface covered by cesium increases toward a monolayer, the dipole action is confined closer and closer to the surface. The force function, acting then on an electron at distances great compared with the average interatomic distance within the cesium film, reverts to the mirror-image function and an experimental evaluation of the increase in electron emission with applied voltage is found consistent with the Schottky line for moderately high fields.

At a given emitter temperature and a given arrival rate of cesium atoms, the population of atoms on the surface and their dipole moment per atom will be sensitive to the underlying true work-function associated with a specific crystallographic orientation of the tungsten surface. Again it is the true work-function that strongly influences these surface properties and finally it is the true work-function of the surface modified by the absorption of polarizable atoms that determines its emission properties, its ionization capability, and its surface potential. The latter now plays a strong part in determining the potential distribution in the inter-electrode space, the electron or ion trajectories and their energy distribution.

Effective Work-Function

Although Eq. 7 gives the random current density in the immediate neighborhood of a surface characterized by a temperature T and a true work-function ϕ, it is seldom true that a measured current density in some specific experiment can be set equal to that expected according to Eq. 7 and in that manner solve for the true work-function. The reason that this is so difficult is that in many cases the precise area which is delivering the actual measured electron current may not be known and the macroscopic current measured may come nonuniformly from the emitter because of a nonuniformity in the true work-function. Some areas may be delivering "saturation emission" whereas other areas may be space-charge limited. It is nevertheless very often helpful to use the equation form given as Eq. 7 to relate an observed current to an effective work-function as follows:

$$i_{ob} = a \cdot 120 \cdot 10^4 \, T^2 \, e^{-\frac{\phi_{eff}}{V}} \quad \text{amp.} \qquad \Big| \; 8$$

If the observed current density is defined as (i_{ob}/a) even though the emitting surface may not be uniform and the true emitting area not known, it is nevertheless possible to use the available facts to evaluate an effective work-function ϕ_{eff}. This computation results in

$$\phi_{eff} = 2.303 \, V \left[6.08 + 2 \log_{10} T - \log_{10} I_{ob} \right] \qquad \Big| \; 9$$

From this relation the "effective work-function" may be defined as "The value of the empirical constant defined by Eq. 9 which relates an experimental value of observed current density to the temperature." This statement may be reworded as "The value of ϕ needed in Eq. 7 which would be the true work-function if the observed current density were the actual equilibrium current density at the surface of the emitter."

Richardson Work-Function and The Thermionic Constant

As a result of the application of quantum thermodynamics to the problem of thermionic emission, Dushman(3) and others evaluated the constant of an equation similar to Eq. 7 at 60 amp/cm^2-deg^2. At the same time they agreed with Richardson's earlier analysis that indicated that this number should be a universal constant. Later developments showed that the Dushman theory was in error by a factor of 2 and had he known that statistical weight associated with an electron should have been 2 because of an electron spin, the recognized theoretical thermionic constant would have been 120 and not 60. It was a pure accident therefors that the earliest reasonably accurate experimental determination of the thermionic emission from tungsten surfaces yielded an empirical constant of 60. For some years this result was taken ~~as~~ to indicat~~ive~~e that the tungsten work-function was really a constant and that the theoretically-~~determined~~ computed thermionic constant A had been established by experiment. Later studies have shown that emission from tungsten samples of the type used by Dushman is very nonuniform and furthermore that the true work-function of the various crystals has different values and different temperature coefficients. Assume for the purposes of this discussion that the true work-function used in Eq. 7 can be expanded by the following power series

$$\phi = \phi_0 + \alpha\overline{V} + \beta\overline{V}^2 + \gamma\overline{V}^3 + \dots \qquad (10)$$

In this equation ϕ_0 is the true work-function at absolute zero and the coefficients α, β, γ ... may have positive or negative numerical values so that the power series expansion really represents the true work-function at any temperature. Assume for the purposes of this discussion that the relation represented by Eq. 10 is shown by the graph of Fig. 1. The solid line in Fig. 1 has been drawn in an arbitrary manner in order to illustrate the distinction which must be made between the true work-function at zero degrees and the Richardson work-function. Here it is assumed that the true work-function at any temperature is shown by the solid line. An experiment typical of those done over the past 40 years may relate to the temperature range between $\overline{V}_1$ and $\overline{V}_2$. The true work-function over this range may be represented with reasonable accuracy by the following formula

$$\phi = \phi_R + \alpha_R\overline{V} \qquad (11)$$

It is to be emphasized that ϕ_R is not the true work-function at absolute zero and the a_R bears no direct relation to the a of Eq. 10. The insertion of Eq. 11 into Eq. 7 yields an equation often identified as the "Richardson equation."

$$I = 120 \times 10^4 e^{-a_R} T^2 e^{-\frac{\phi_R}{V}} \qquad 12$$

The test usually used to evaluate the empirical constants of Eq. 12 involves the measurement of thermionic emission current from a specimen of unknown distribution in true work-function and unknown area. The experimenter may not admit this and therefore he observes a certain total current that arrives from an emitter under a strong field condition and divides that current by the superficial area of the emitter and calls it the "saturation" current. He may do this over a range of applied voltage and at each temperature, plot the logarithm of the current as a function of the square root of the voltage. He calls this a "Schottky plot."(4) The data points generally do not fall on a straight line but he choses some representation that he considers to be straight over a sufficient range to extrapolate linearly to zero applied voltage. The current density thus measured is divided by the square of the temperature and ~~its~~ the logarithm [illegible] is plotted as a function of V^{-1}. Very often the resulting plot is a straight line over the limited range in temperature for which the experiment can be carried through. From the slope of this line a suitable value for ϕ_R is obtained. Any point on the line may now be used to compute a second empirical constant A_R so that Eq. 12 seems to take on the form

$$I_{ob} = A_R T^2 e^{-\frac{\phi_R}{V}} \qquad 13$$

In this manner the two numbers needed in Eq. 13 may be established. Without knowledge concerning the details of emitter uniformity it is not legitimate to identify the difference between A_R and the universal thermionic constant A defined by Eq. 14 as a direct measure of the true temperature coefficient of the work-function through the factor exp $(-a_R)$.

$$A = \frac{2\,q(2\pi mk^2)}{h^3} = 120 \times 10^4 \text{ amp/m}^2 \cdot (\text{deg K})^2 \qquad 14$$

In practically all listings of the thermionic constants(5) determined by the Richardson plot method, the work-function values ϕ_R and the thermionic constant A_R have no significance beyond the fact that they yield a correlation of the observed apparent current densities and the temperature. No reliance can be put on values of the Richardson work-function determined in this manner if the purpose is the choice of a work-function to serve for the determination of surface potential, surface density of charge, or ionization production. The true work-function is needed as a basis for the correct understanding of the properties of a thermionic converter and not the Richardson work-function.

Summary of Work-Function Definitions

1. The true work-function is the energy difference between the Fermi Level and the electron energy approximately 1/10th of a micron away from the surface.

2. The effective work-function is determined by the emission properties of an emitter idealized as though it had a true work-function equal to the effective work-function even though the exact distribution of true work-function over the surface and the exact area contributing effectively to the observed emission are not known.

3. The Richardson Work-Function is an empirical constant suitable for use in Eq. 13 as a means of correlating some observed apparent current density data with the temperature.

"Emitter-Collector" vs. "Cathode-Anode"

In conventional vacuum tubes the terminology "cathode," "control grid," "screen grid," "suppressor grid" and "anode" are some of the terms well established by tradition. Furthermore, these terms are in themselves consistent with the dominant function even though the cathode is not specifically a receiver of cations (positive ions) since its more important function is to emit electrons. The anode, however, does receive negative ions if we are satisfied to identify the electron as a negative ion.

In the diode and especially the diode used for the direct conversion of heat to electricity, the application of words more or less suitable to vacuum tube terminology is somewhat less app~~licable~~ropriate. When I prepared my article on "Thermionic Emission" in 1954-1955, it was my opinion that the words "emitter" and "collector" were more applicable since the predominant function of the heated electrode is to emit electrons and the predominant purpose of the other electrode is to collect them. The surface potential of the collector is often negative with respect to the surface potential of the emitter. It is important in the understanding of thermionic emission to study voltage-current curves over the entire range of collector surface potential from that of being moderately negative with respect to the emitter to being strongly positive with respect to it. This diode element identified as the "collector" in contrast to the "emitter" may itself be an emitter if its surface potential is negative with respect to the normal emitter and the temperature of the collector is permitted to go high enough. This back current can influence the voltage-current characteristic.

In the plasma diode used for direct conversion the situation is still more complicated. There again the predominant function of each of the electrodes is for one to be an electron emitter and the other an electron collector. Under some methods of operation, both become collectors of positive ions. The emitter may become a generator of ions depending on its work-function and temperature, and the collector may receive as many positive ions as it does electrons under the condition of the open circuit voltage determination of a plasma diode. Thus the function of the collector is not just that of receiving "anions" which in vacuum tube practice ~~is~~ as mentioned above ~~and~~ implies that the electron is a "negative ion." It also receives cations. It is in recognition of these points that the present writer prefers to separate the terminology from that conventionally used in the vacuum tube industry. The terminology proposed here as being more functional in the concepts the "emitter" and the "collector" are not completely unambiguous but nevertheless define the elements of the diode with respect to their principal function.

MOTIVE AND POTENTIAL DIAGRAMS

It is with the help of diagrams and words that scientists communicate. Also they provide a second function which does not involve the communication of one scientist to another. This function is the organization of ideas for an individual. There is no "right" or "wrong" way of satisfying these criteria as long as the words and diagrams are self-consistent and unambiguous. Sometimes the misuse of a diagram leads to misunderstanding and therefore it is extremely important to recognize a diagram for what it is. The facts to be brought out by the diagram must be clearly formulated and the boundary conditions defined.

As a means of communication in electronics, motive diagrams are extremely useful. The importance of the concept of "motive" has been recognized by very few writers and is therefore most familiar to those who have followed the teachings of Langmuir, Bridgeman, and a few others. The Langmuir$^{(6)}$ definition of motive is: "The motive is thus defined as a scalar quantity whose gradient in any direction and at any point represents the force component per unit charge which must be applied to an electron or an ion to hold it in equilibrium at the given point." Note that this definition does not imply the holding of all other charges in position as one measures the work required to change the position of the electron or ion which in turn is the line integral of the force acting on it. Stated more simply, this means that a motive diagram can be drawn to represent the variation in the effective potential energy of an electron as it traverses from the interior of a metal out through the surface barrier. This barrier is dominated at an extremely close range by the properties of the atoms themselves and dominated at larger range by the mirror-image forces discussed in this memorandum. In general, the actual location of the internal potential of a solid in such a diagram is less important than the determination of a suitable reference line which is identified as the "Fermi Level."

A motive diagram designed to emphasize in some detail the motive transition at the border line between a conducting metal and an evacuated space is drawn in Fig. 2. The motive diagram is the heavy solid line. To the left of the demarkation line the motive schematic shows periodicity to suggest the location of atoms within the solid. The lighter line from which the two arrows W_i and W_a are drawn represents an approximate average at the level of the periodic motive function. There are very few experiments for which the absolute value of the difference in energy between this average and the Fermi Level is important. The quantity W_a then represents the change in motive from its average value in the interior to its more clearly defined value at the surface of the conductor. In view of the discussion above, "at the surface of the conductor" implies a distance out into the evacuated space of between 100 and 1000 angstroms or about 0.1 micron. The true work-function of this surface is identified as ϕ and is related to the other quantities by:

$$\phi = \frac{W_a - W_i}{q} \qquad (15)$$

In this diagram the vertical scaling from the average motive in the interior of the metal represents the kinetic energy associated with the motion of an electron in the direction perpendicular to the surface barrier. This direction may be taken as the "x" direction and the motive function then takes on the interpretation that it represents the potential energy of an electron. This energy is a function of x only. Available electronic states exist anywhere in the diagram above the motive diagram line and the separation between any chosen energy state and the solid motive line is a direct measure of the kinetic energy associated with the motion in the x direction. This diagram does not permit the display of kinetic energy associated with motion transverse to the x direction. The Fermi Level is identified by the fact that in quantum physics some of the energy levels are fully occupied and other available levels are not occupied. The Fermi Level identifies that level for which the probability of occupancy is 50 per cent. In general as the temperature increases, the Fermi Level relative to the average interior potential and identified by the energy W_i decreases. It is also anticipated that the motive step represented by W_a decreases with increasing temperature. Whether or not the true work-function decreases or increases depends on the relative rates of change of W_i and W_a. These remarks were made concerning the motive diagram in Fig. 2 in order to give an illustration of its use.

Another type of motive diagram is to be found in practically all books related to the theory and application of vacuum tubes. In this motive diagram the principal emphasis is on the distribution of potential (identical with the motive at large distances from surfaces). The reference in this diagram at $x = 0$ is the surface potential at the emitter. The straight line represents the solution to Laplace's equation for a plane parallel diode of width w when the surface potential of the collector is positive with respect to that of the emitter. If these surface potentials are maintained and the emitter begins to deliver electrons to the collector, then the motive diagram shifts as the electron current increases to curve B from curve A. Any shift away from curve A implies that there are an appreciable number of electrons in transit to alter the motive function. In terms of boundary conditions of emitter capability and temperature, Langmuir(7) has shown that it is possible to obtain a solution of Poisson's equation consistent with a Boltzmann energy distribution of the electrons and consistent with the equation of continuity.

This motive diagram of Fig. 3 has been reproduced over and over again in the electronic literature and is familiar to practically all students of the subject. The objection to it is that it does not emphasize the need to know the work-function of the emitter and the work-function of the collector in order to obtain a correct solution for Poisson's equation consistent with the requirements of the experiment. The motive diagram of Fig. 3 supplemented as is shown in Fig. 4 satisfies all of the needs. Even though no change has been made in passing from Fig. 3 to Fig. 4 in the nature of the motive function in the space in between the emitter and the collector, the diagram is now more complete in that it shows clearly, the value of the applied difference in potential and its relation to the emitter work-function ϕ_1 and the collector work-function ϕ_2. A comparison between Fig. 2 and Fig. 4 may lead some readers to feel that Fig. 4 is "upside down," whereas the real difference between them is that the space part of the motive diagram is the important part and its association with the observable applied voltage with the help of the work-function values combines diagram 2 with diagram 3 and necessitates the inversion of diagram 2.

One other aspect is of importance in diagram 4 which is that electronic energy states all lie <u>below</u> the heavy motive line. Since this diagram can also serve to describe the potential energy and kinetic energy of the positive ions that might be present in a diode, the statement may be made that <u>positive ion states all lie above the heavy motive line.</u> ∧ There is no way to show the potential energy of a neutral atom on a motive diagram. Figure 5 is a second example of a motive diagram applicable to a plasma converter showing again the main factors needed in a proper discussion of this device and their relation to electrons, ions, space-charge sheaths, work-functions, etc.

Figure 5 shows qualitatively the distribution in motive from the surface of the emitter to the surface of the collector including the Fermi level reference to these surface potentials given by their respective work-functions. The diagram shows the Fermi Level of the collector to be negative with respect to the Fermi Level of the emitter and amount V. A positive ion space charge exists both at the emitter surface and the collector surface and positive ions can occupy energy states represented in this diagram which lie above the solid line. The electronic energy states all lie below the solid line.

These paragraphs are written in this report in order to bring forward for future discussion the convention adopted by this writer and the basic reasons for it. It is hoped that others will attempt to evaluate these reasons or present good arguments to indicate that other conventions than those promoted here are less ambiguous or more informative in order to justify departure from tradition.

CURRENT-VOLTAGE CURVES

Again we refer to the practice that has been established broadly in the electronics industry of using the Fermi level of the emitter as the reference for potentials. If the Fermi level of the collector is made positive with respect to the emitter, it is shown diagrammatically as a potential measured out to the right of zero potential. See Fig. 6. This is interpreted as positive applied potential. On the other hand if the collector Fermi level is negative with respect to that of the emitter then observed currents are associated with potentials located along the abscissa to the left of the origin. In the vertical direction, the arrival of electron current at the collector is generally identified by measuring a distance, again from the origin, upward. If there is electron emission from the collector due to photoelectric effect or thermionic emission from the collector, the current values are plotted below the line. Positive ion arrival at the collector is also represented graphically by placing its measure below the line. In such a diagram the use of the conventional vacuum tube practice identifies the "energy conversion quadrant" to be the upper left-hand quadrant of the diagram. The presentation of data in a manner consistent with this convention is not always used by the active groups now interested in thermionic conversion.

It is the present writer's view that although no harm is done by deviating from this convention, there is relatively little advantage in the deviation and in some cases it is necessary to analyze the curves used in a particular display to be sure what convention the particular writer is using. Again the most important feature is that the writer should be completely unambiguous and not take it for granted that his reader will interpret his convention correctly especially if he deviates from that traditionally established in the general field of thermionics and its applications.

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3. S. Dushman, Phys. Rev. 21, 623 (1923).

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5. "Thermionic Emission" above, page 175.

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Figure Captions

Fig. 1 Example of the variation of the true work-function with temperature. (solid line). Approximate representation between $\bar{V}_1$ and $\bar{V}_2$ (dashed line).

Fig. 2 Motive diagram for metal to vacuum surface.

Fig. 3 Motive diagram in a diode. A. Laplace solution (no space charge). B. Poisson solution space-charge limited.

Fig. 4 Motive diagram of Fig. 3 completed to show its relation to the Fermi levels of the emitter and collector.

Fig. 5 Motive diagram of a plasma thermionic converter.

Fig. 6 A voltage-current curve of a cesium thermionic diode.

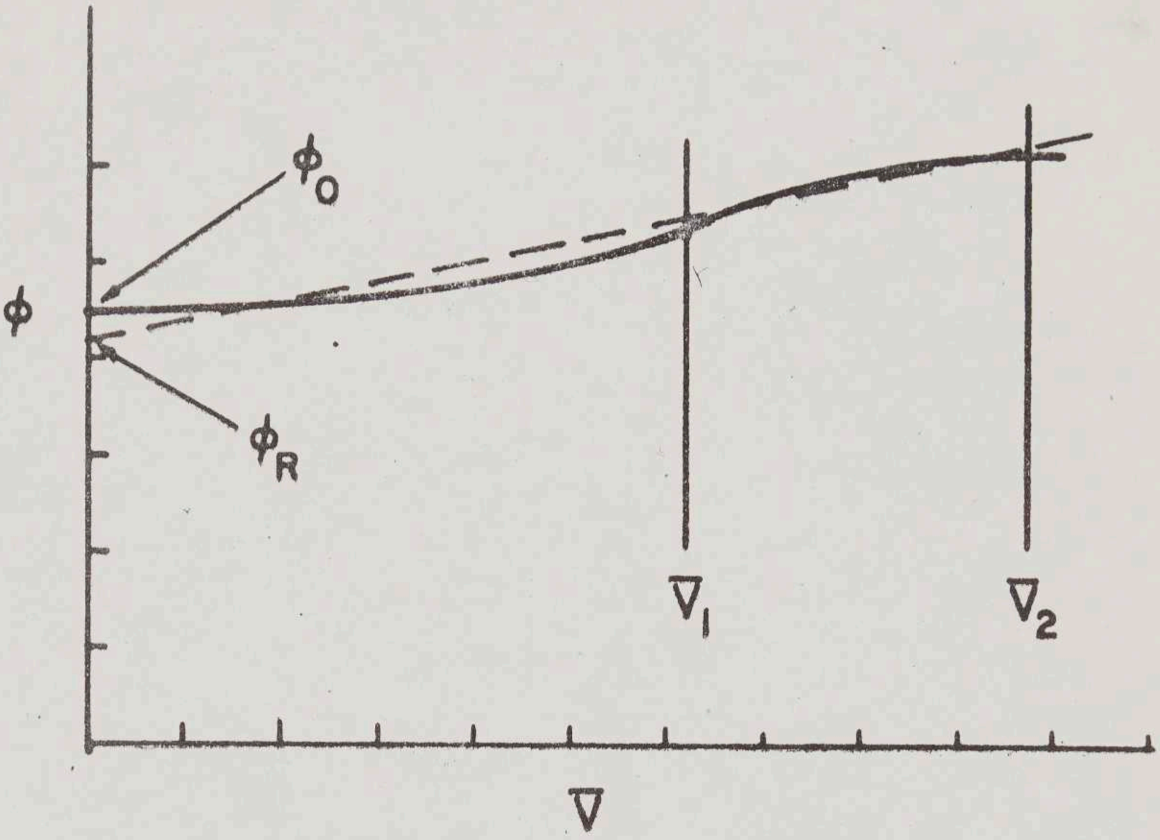

Fig. 1

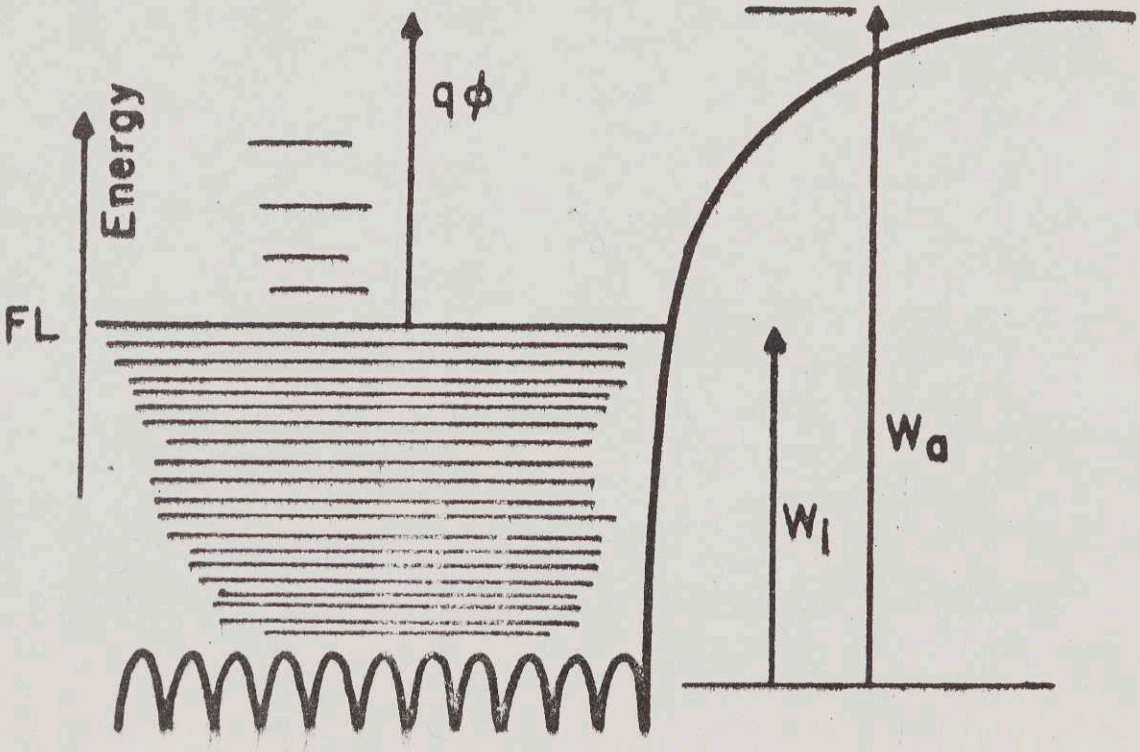

Fig. 2

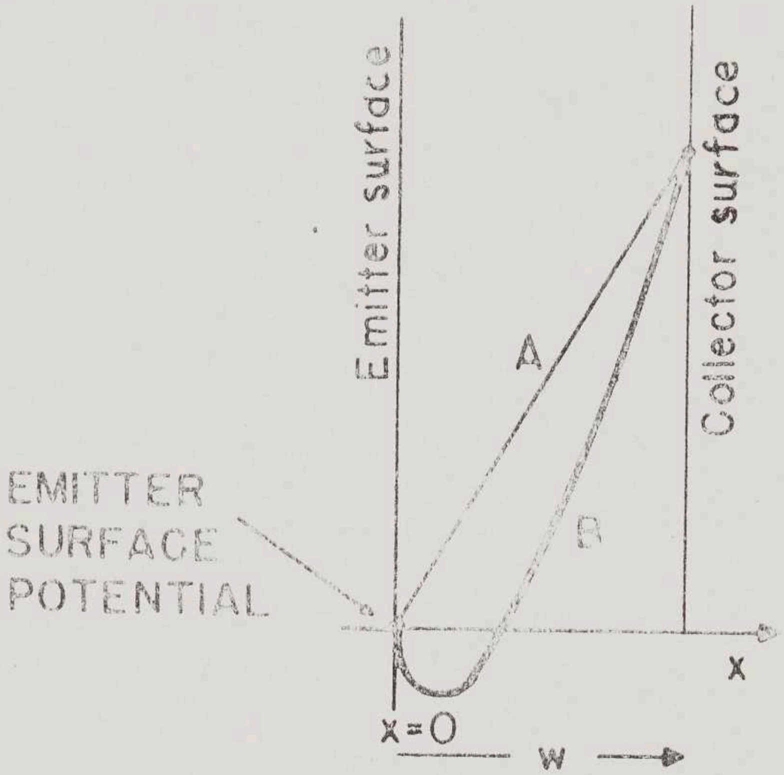
Emitter surface
Collector surface
A
B
EMITTER
SURFACE
POTENTIAL
x
x=0
w

Fig. 3

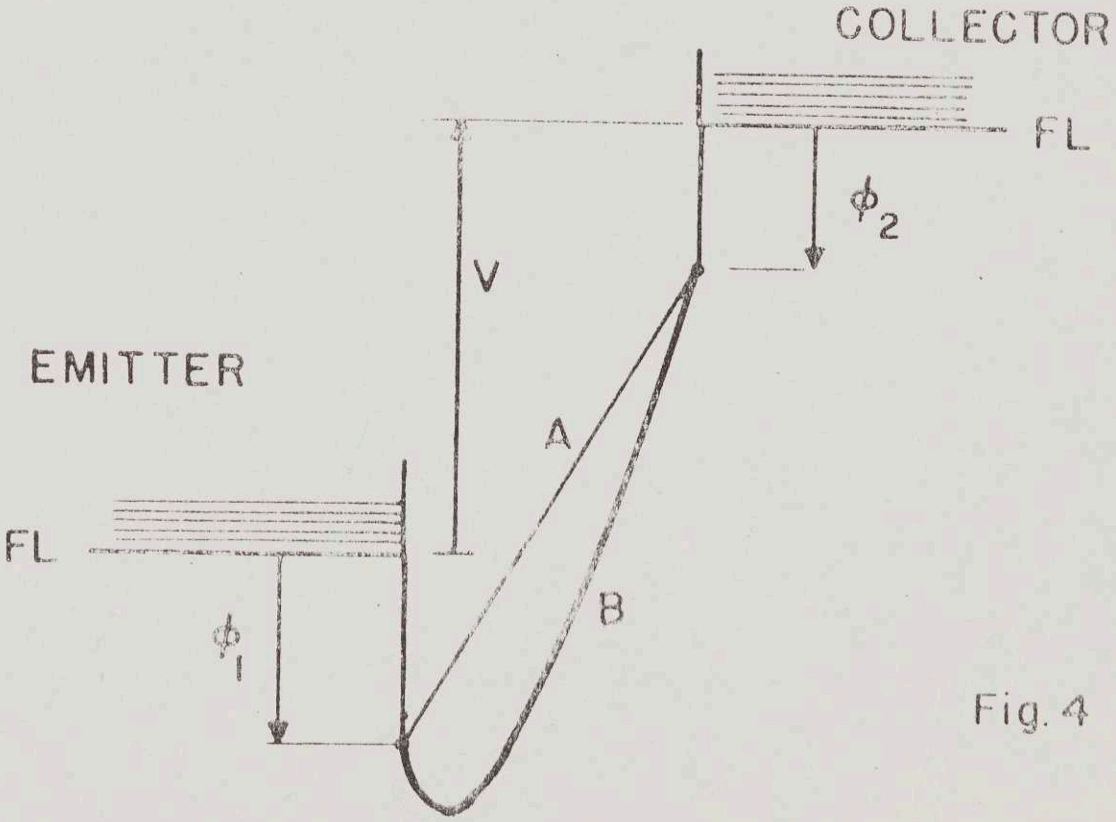
COLLECTOR
FL
ϕ_2
V
EMITTER
A
B
FL
ϕ_1

Fig. 4

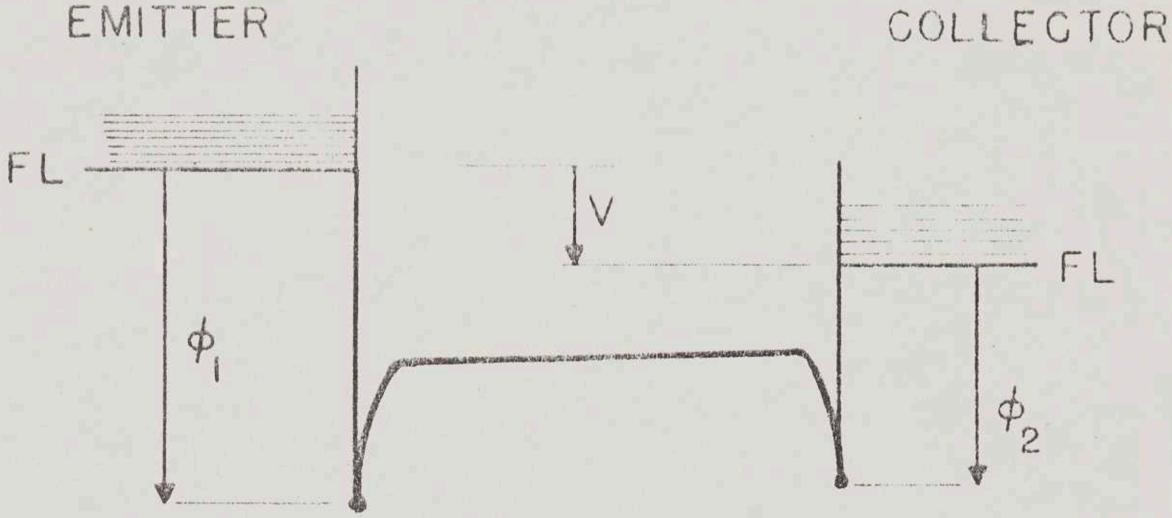
EMITTER
COLLECTOR
FL
V
FL
ϕ_1
ϕ_2

Fig. 5

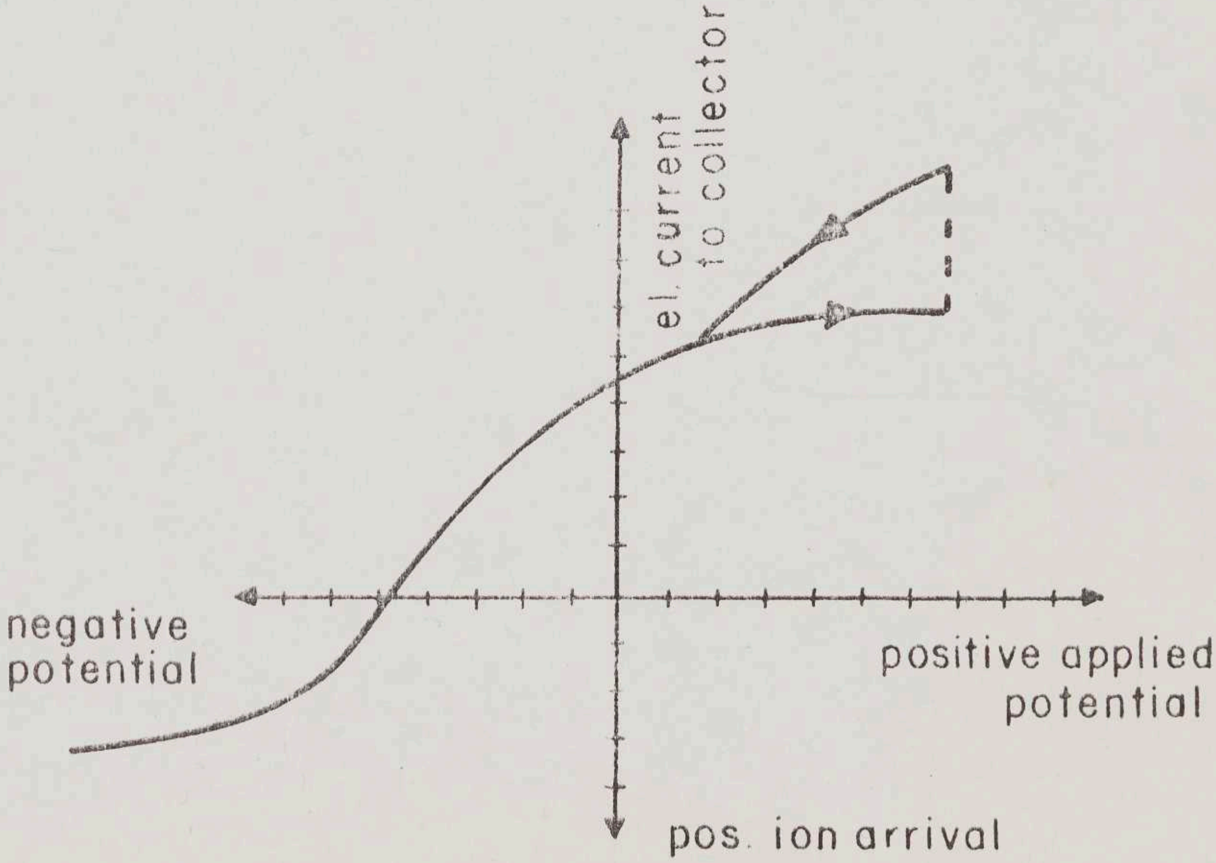
el. current to collector
negative potential
positive applied potential
pos. ion arrival

Fig. 6