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SOME INTERACTIONS OF POLYCRYSTALLINE TUNGSTEN ELECTRODES WITH CESIUM PLASMAS

by James F. Morris

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Cleveland, Ohio

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ABSTRACT

At thermionic-diode temperatures, work functions of tungsten electrode surfaces depend strongly on positive-ion sheaths between these electrodes and cesium plasmas. The present theoretic study demonstrates this effect for a plane field-modified emitter with a collisionless positive-ion sheath in a thermally ionized plasma. The analysis covers temperatures from 1700 to 2600 K; plasma electron number densities of 10^{12}, 10^{13}, and 10^{14} cm^{-3}; and a bare work function of 4.59 V. Values for sheath voltages, work functions, and cesium arrival rates and coverages on tungsten result from equilibrium calculations. In addition to these variables, computations for elevated plasma electron temperatures yield net current densities. Throughout this work, the sheath drops lie below 1 V. And atom arrival rates approach total cesium arrival rates only at low temperatures and sheath voltages.

STAR Category 25

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SUMMARY

Positive-ion sheaths greatly influence surface properties of polycrystalline tungsten at thermionic-diode temperatures in cesium plasmas. Indications of this effect on work functions come from the present analysis; here, plane field-modified emitters of electrons, ions, and atoms obtrude collisionless positive-ion sheaths into thermally ionized plasmas. For calculations based on these components, temperatures range from 1700 to 2600 K; cesium plasmas contain 10^{12}, 10^{13}, and 10^{14} electrons per cubic centimeter; and the bare polycrystalline tungsten has a 4.59-volt work function. Equilibrium sheath solutions yield overall voltages, cesium arrival rates and coverages on the electrodes, and work functions. These variables as well as net current densities result from computations for plasma electrons up to 200 K hotter than the other constituents.

The generalized sheath properties follow correlations given in previous publications on this model: They apply only for equilibria, near equilibria, and relatively low net transport. They are functions of the plasma electron number density N_{eP}, the absolute temperature of the electrode T_E, the work function minus the plasma potential, and the emission Debye length, $\lambda_{DE}(\mathrm{cm}) \approx 6.9\left\{\left[T_E(\mathrm{K})\right]\Big/\left[N_{eP}\left(\mathrm{cm}^{-3}\right)\right]\right\}^{1/2}$. And they result from sheaths with effective widths of approximately 2 to $2\frac{1}{2}$ emission Debye lengths.

Previous studies with parametric work functions revealed no restriction of sheath voltages. But the present analysis with work functions affected by cesium adsorption produces sheath drops below 1 volt only. This limit derives from restricted ionization at the electrodes. Inhibited ion production occurs because of reduced work functions at low temperatures and because of decreased cesium arrivals at high temperatures even with increased work functions. When the sheath drops as well as the temperatures are low, atoms reach the electrodes at rates approaching those for total cesium arrivals. Otherwise adsorption of the ions generally outruns that of the atoms by over an order of magnitude. Positive-ion sheaths in cesium plasmas definitely react to and strongly affect electrode work functions.

INTRODUCTION

References 1 to 4 develop theories for plane collisionless sheaths separating thermally ionized plasmas (ref. 5, Saha) from field-modified emitters of electrons, ions, and atoms (refs. 6 to 9: Richardson, Dushman; Saha, Langmuir; and Schottky). These models for positive-ion and electron sheaths apply for equilibria, near equilibria, and relatively low net transport. The previous investigations (refs. 1 to 3) for parametric variations of work functions, temperatures, and plasma electron concentrations give sheath characteristics for cesium plasmas. As references 1 to 3 note, however, cesium changes electrode work functions and makes coincidence of the parametric and actual work functions fortuitous. The present study overcomes this theoretic deficiency. It reveals effects of adsorption on work functions of polycrystalline tungsten surfaces with positive-ion sheaths in cesium plasmas.

Collisionless sheaths pass atoms freely but alter ion transport, hence adsorption, and therefore surface potentials like work functions. In electron sheaths, emitted ions accelerate into the plasma, while ions moving toward the electrode decelerate and often reflect. Then the electron sheath reduces the total arrival rate of the plasma chemical, ions and atoms (ref. 10). For plasmas with low degrees of ionization, though, electron sheaths affect adsorption only slightly. If conditions require solutions for electron sheaths, a direct procedure yields them. The sum of atom and ion fluxes leaving the plasma serves as an approximate arrival rate for an estimate of the work function (ref. 11). With this work function, the emitter temperature, and the plasma conditions; references 1 to 3 allow a good guess at the overall sheath voltage. The sheath drop in turn yields a correction for the ion arrival rate, then for the work function, and again for the sheath drop. Finally a close approximation of the emitter, sheath structure evolves. Because of this simple iterative method and the overwhelming interest in positive-ion sheaths, the present analysis bypasses the solution for electron sheaths.

But the positive-ion sheath complicates determinations of arrival rates at electrodes (ref. 10). And because this sheath traps many ions at the electrode surface, atom fluxes alone from plasmas with low ionization often approximate total arrival rates poorly. In positive-ion sheaths, plasma ions accelerate to the electrode, while emitted ions decelerate toward the plasma and often return to the emitter. Such movements oppose those in the electron sheath, where total arrival rates depend only on the sheath drop and the ion and atom fluxes from the plasma. In addition to their dependence on these three variables, however, total arrival rates for positive-ion sheaths are functions of three more: the ionization potential of the plasma chemical; the sheath field at the electrode; and the work function, which varies with surface coverage (ref. 12). The present method combines the total arrival rate with a work function correlation (ref. 11) in another iterative loop on the original solution for positive-ion sheaths (refs. 1 to 4). Now the machine solves for the cesium-ion sheath properties for a specified plasma and bare polycrystalline tungsten, obtains the total cesium arrival rate for that solution, corrects the work function for the cesium coverage on the tungsten electrode, computes the sheath properties for the new work function, and continues to iterate to a final answer. Without output plots (refs. 1 to 4), a complete solution requires about 0.03 minute on an IBM 7090.

In the previous discussion relating cesium arrival rates to work functions, references 11 and 12 appeared. Many other papers give theories for adsorption effects on surface potentials, but these two are unique. Reference 12 presents perhaps the best general solution for this problem thus far; it relates surface properties to coverages. As reference 10 indicates, though, desorption times and energies for ions and atoms are prerequisites for determinations of surface coverages from arrival rates. These desorption data vary with coverage and result only from well-controlled experiments. At present nothing approaching a complete set of desorption characteristics for an adsorbate on a particular crystal face exists. And although Taylor and Langmuir (ref. 13) published a monumental study of cesium on polycrystalline tungsten long ago, technology now demands definition of crystal orientation. In the absence of better information, however, this report analyzes cesium and polycrystalline tungsten. Furthermore, since reference 11 correlates three sets of cesium and tungsten data admirably (refs. 13 to 15), even though its physical model is questionable, this work uses that correlation for its work function changes. Reference 12 also handles Langmuir's data well but not nearly as precisely or as easily as reference 11.

Further clarification of the terminology and contribution of reference 11 seems necessary at this point. First, "polycrystalline" implies a surface composed of patches of various crystal faces. If these patches are very small compared with the sheath width, the surface is acceptable. This requirement provides the essentially uniform surface potential assumed in the present sheath model. Second, the assumption of a 4.59-volt work function correlates information from references 13 to 15. But the work functions for those references undoubtedly differ from 4.59 volts: Langmuir used a tungsten wire with predominantly 110 surfaces, Houston studied a polycrystalline tungsten, and Breitwieser worked with nearly monocrystalline tungsten having a work function of 5.0 volts. In any event, reference 11 correlates the data of both Langmuir and Houston, both of whom reported work functions very near 4.59 volts.

Thus the present model describes a plane positive-ion sheath separating a thermally ionized cesium plasma from polycrystalline tungsten electrode. The work function varies with surface coverages of the emitter below its bare value of 4.59 volts. Of course cesium adsorption on the tungsten depends on the system properties selected for the analysis: The temperatures run from 1700 to 2600 K with plasma electron temperatures up to 200 K higher than the others; and the plasma concentrations result from 10^{12}, 10^{13}, and 10^{14} electrons per cubic centimeter. From these parameters many detailed results emerge (refs. 1 to 4), but only those that show the effects of the variable work function appear here. Sheath voltages, cesium arrival rates and coverages on tungsten, and work functions alone indicate equilibria. Added to these variables, net current densities reveal the near-equilibrium influences of elevated temperatures for plasma electrons.

Because the basic sheath model remains unchanged (refs. 1 to 3), the previously published correlations of general sheath properties apply to the present study: Dimensionless sheath widths, voltages, and emitter fields and densities of the majority charge at the electrodes depend on the number of electrons in a cubic centimeter of plasma N_{eP}, the kelvin temperature of the emitter T_E, and the work function minus the plasma potential. Since emitted particles dominate this sheath, the plasma Debye length yields as a correlating parameter to the emission Debye length (refs. 1 to 3):

$$\lambda_{DE} \approx 6.9\left(\frac{T_E}{N_{eP}}\right)^{1/2} \tag{1}$$

Most of the sheaths have widths between 2 and $2\frac{1}{2}$ emission Debye lengths at these conditions. In that distance, though, the ion concentration can increase by more than a factor of 100 across a 1-volt sheath. Thus fractional ionization can be low in the plasma but high next to the emitter. Again the positive-ion sheath stands out as a prime influence on cesium arrival rates at electrodes.

SYMBOLS

A, B	constants in equation for cesium vapor pressure
E	sheath field
e	electronic charge (in dimensions consistent with equations in which it is used)
I	ionization potential
j	current density of particle type
m	particle mass
N	number density of particle
p	vapor pressure
T	absolute temperature
ΔV	voltage above plasma potential

θ fractional surface coverage

κ Boltzmann constant

λ shielding length

μ particle arrival rate

$\Delta\varphi$ change in work function

φ work function (without subscript); plasma potential relative to electrode Fermi level (with subscript)

Subscripts:

a atom or atomic

Cs cesium

D Debye

E emission or at emitter

e electron or electronic

i ion or ionic

o plasma potential subscript for near-equilibrium positive-ion sheaths

oo plasma potential subscript for equilibrium sheaths

P in plasma

S across sheath

THEORY

References 1 to 4 detail the thoery for plane collisionless sheaths between emitting electrodes and thermally ionized plasmas. The electrodes emit electrons, ions, and atoms that follow the Richardson, Dushman; Saha, Langmuir; and Schottky relations. And the plasma complies with the Saha equation. References 1 to 3 discuss limitations of the sheath model and generalize results for cesium plasmas and parametric work functions. The present work incorporates a polycrystalline tungsten emitter with work functions that depend on the amount of its surface covered by cesium.

For the positive-ion sheath, the arrival rate of the plasma chemical is

$$\mu = \frac{j_{aP} + j_{iP} + j_{iE}\left[1 - \exp\left(-\frac{e\Delta V_S}{\kappa T_E}\right)\right]}{e} \tag{2}$$

where ΔV_S is a positive number. Ionic and atomic current densities (j_{iP} and j_{aP}) pass unchanged from the plasma through this sheath to the emitter. Because no exponential cutoff of the ion flow occurs, equation (2) imposes no particular form of velocity distribution on the ionic and atomic streams from the plasma. But current densities of emitted ions j_{iE} experience exponential cutoffs and particularlly reflect back to the emitter surface. Therefore, equation (2) requires half-Maxwellian ionic emission, which is what the thermal emitter provides. Thus, equation (2) stands essentially unrestricted for cesium on tungsten.

For the present model of a positive-ion sheath, ionic emission involves the ionization potential I and current densities of the plasma atoms and ions in addition to the voltage across the sheath and the electrode properties: the absolute temperature T_E, work function φ, and sheath field E_E (refs. 1 to 3):

$$j_{iE} = \frac{j_{aP} + j_{iP}}{2 \exp\left[\dfrac{e(I - \varphi) + \left(e^3 E_E\right)^{1/2}}{\kappa T_E}\right] + \exp\left(-\dfrac{e\Delta V_S}{\kappa T_E}\right)} \tag{3}$$

Substituting this expression into equation (2) yields equation (9b) of reference 10:

$$\mu = \frac{j_{aP} + j_{iP}}{e} \frac{1 + 2 \exp\left[\dfrac{e(I - \varphi) + \left(e^3 E_E\right)^{1/2}}{\kappa T_E}\right]}{\exp\left(-\dfrac{e\Delta V_S}{\kappa T_E}\right) + 2 \exp\left[\dfrac{e(I - \varphi) + \left(e^3 E_E\right)^{1/2}}{\kappa T_E}\right]} \tag{4}$$

Total arrival rates come from equation (2) because of the use of results from the calculations for positive-ion sheaths (refs. 1 to 4). Both ionic and atomic cesium arriving at the polycrystalline tungsten surface contribute to its fractional coverage θ, and this in turn leads to a work-function change $\Delta\varphi$. But reference 11 bows to a tradition of thermionics and represents the arrival rate with a cesium reservoir temperature T_{Cs}. When this reference uses a logarithmic term for effects of ion adsorption, the correlation fails at low coverages. Thus, the present work relies on the simple effective version (eqs. (10) and (17) of ref. 11):

$$\Delta\varphi = \frac{-8.75\,\theta}{1 + 1.77\,\theta^{3/2}} \qquad 0 < |\Delta\varphi| < 2.88\ \mathrm{V},\ 0 < \theta < 0.6 \tag{5}$$

$$-1.37 - 1.34\left(\frac{\Delta\varphi}{8.75\,\theta}\right)^2 = \frac{T_E}{T_{Cs}}\left(-\frac{B}{11\,606} + \frac{T_{Cs}}{11\,606}\left\{A + \ln\left[\frac{7.02\times10^{-6}(1-\theta)}{T_{Cs}^{1/2}\theta}\right] - \frac{1}{1-\theta}\right\}\right) \tag{6}$$

Between θ values of 0.6 and 0.8, $\Delta\varphi$ equals about 2.88 volts.

In reference 11 the constants A and B appear in an expression that correlates Taylor and Langmuir's vapor-pressure data for cesium in millimeters of mercury (multiply by 133.3224 for N/m^2):

$$\ln p_{Cs} = A - \frac{B}{T_{Cs}} \tag{7}$$

The values of the constants A and B are given in the following table for various cesium reservoir temperatures.

Cesium reservoir temperature, T_{Cs}, K	Constants in eq. (7)	
	A	B, K
224 to 302	17.70	9300
302 to 408	16.17	8820
408 to 551	15.76	8660
551 to 745	15.38	8440

Only T_{Cs} remains undefined; it depends on the arrival rate of equation (2):

$$T_{Cs} = \frac{1}{2\pi m_{Cs}\kappa}\left(\frac{P_{Cs}}{\mu}\right)^2 \tag{8}$$

With these equations and the solution for the positive-ion sheath, the calculations form a standard iterative pattern:

(1) Select temperatures for the electrode and plasma and assign the plasma electron

concentration.

(2) Compute sheath results for $\varphi = 4.59$ volts (refs. 1 to 4).

(3) Determine the total cesium arrival rate (eq. (2)).

(4) Calculate T_{Cs} (eqs. (7) and (8)).

(5) Obtain θ and $\Delta\varphi$ (eqs. (5) and (6)).

(6) Add $\Delta\varphi$ to 4.59 volts to give a new φ.

(7) Average the new and previous values of φ.

(8) Compute sheath results for the new average φ.

(9) Iterate steps (3) to (8) until φ changes by less than 0.001 volt.

This cycle with the separate sheath iteration in it produces complete emitter results and a detailed sheath description in about 0.03 minute on an IBM 7090 computer. The complete calculation procedure appears in reference 16.

DISCUSSION OF RESULTS

Figures 1 to 5 evolve the effects of collisionless positive-ion sheaths on plane polycrystalline tungsten surfaces in cesium plasmas. In parts (a) of the figures equilibrium results appear; for the (b) parts and figure 5 the plasma electron temperature runs up to 200 K hotter than that of the rest of the system. Plasma concentrations derive from thermal ionization by 10^{12}, 10^{13}, and 10^{14} electrons per cubic centimeter. Temperatures range from 1700 to 2600 K giving pressures between 10^{-4} and 10 torr (multiply by 133.3 for N/m^2). And the electrodes with bare work functions of 4.59 volts emit ions, electrons, and atoms with effective work functions influenced by the sheath fields and adsorbed cesium on their surfaces. The results presented in figures 1 to 5 and any generalization based on them apply only for these conditions with the restrictions given in the preceding sections and the previous publications on this sheath model (refs. 1 to 3). For the present results the selected temperatures prevent electrode melting, the Debye lengths are shorter than 1 mean free path for cesium charge exchange, and the net particle current densities remain below 6 percent of their respective random plasma fluxes.

Figure 1(a) shows overall sheath voltages for work functions of polycrystalline tungsten with adsorbed cesium and for a constant work function of 4.59 volts. If the work function were always 4.59 volts, the sheath drop would rise with the plasma electron concentration at any fixed temperature. But actually the work functions climb or fall with increasing electron number densities depending on the temperature. For a given plasma electron concentration, the overall sheath voltage passes through a maximum as the system grows hot. With greater electron concentrations these extrema occur at high temperatures and appear lower and flatter. At high temperatures the sheath voltages

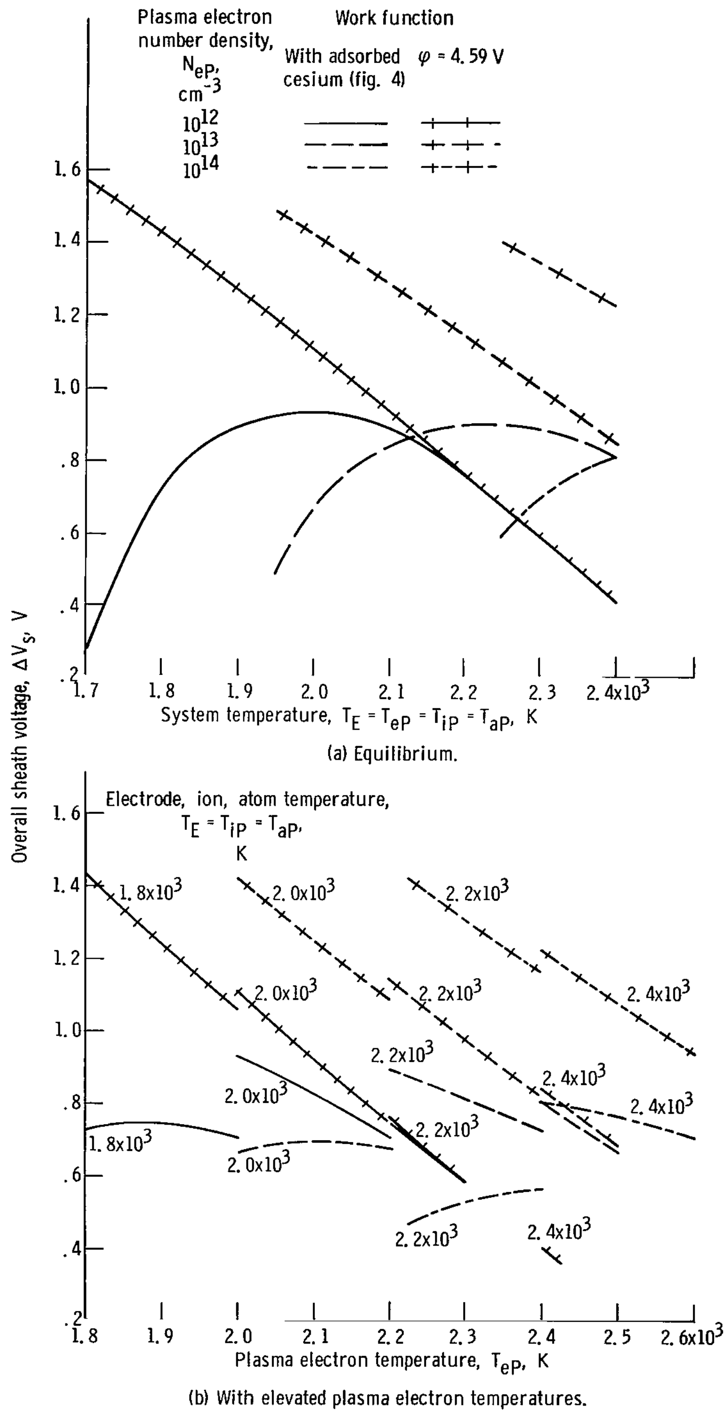
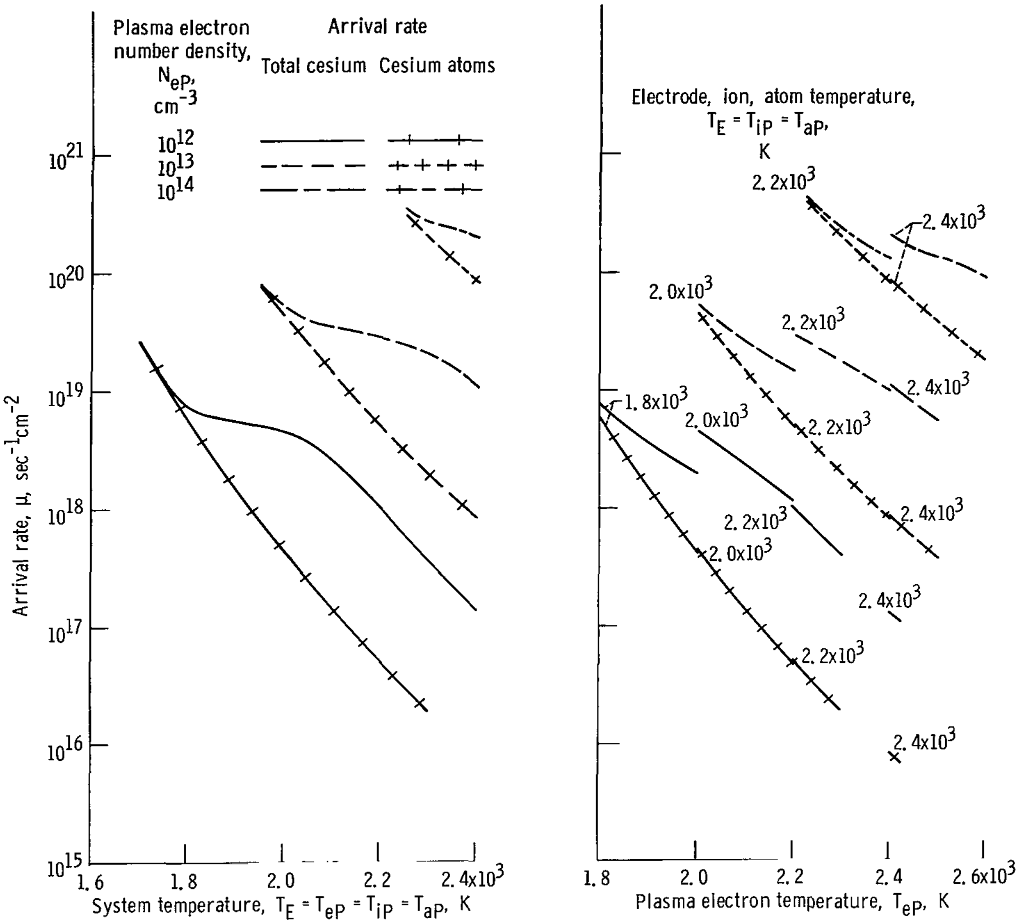


Figure 1. - Potential drops across positive-ion sheaths separating cesium plasmas (Saha) from plane polycrystalline tungsten surfaces (φ = 4.59 V).



(a) Equilibrium.

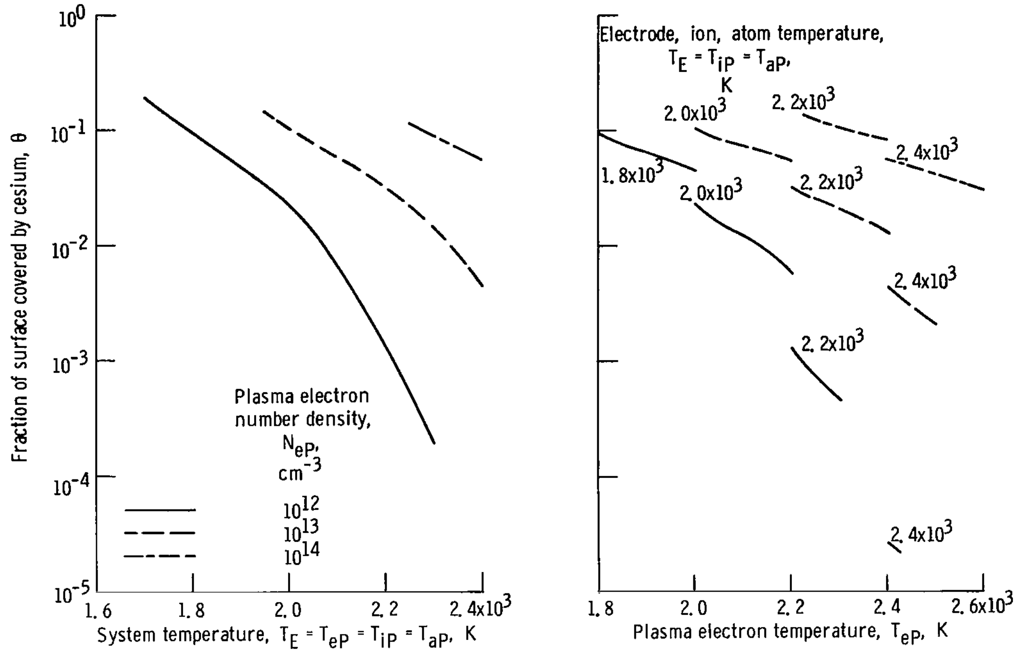
(b) With elevated plasma electron temperatures.

Figure 2. - Cesium arrival rates at plane polycrystalline tungsten surfaces (φ = 4.59 V) separated by positive-ion sheaths from plasmas (Saha).

approach those for a 4.59-volt work function. For these conditions, however, the true sheath drops never reach as high as 1 volt. Discussion of figures 2 to 5 indicates some reasons for this limit.

Figure 2(a) reveals a similarity of atomic and total arrival rates only at low temperatures. When the system grows hotter, the arrivals of ions outnumber those of the atoms by over 10 to 1. Thus the cesium reservoir temperature generally fails to represent cesium arrival rates properly in a thermionic diode operating at these conditions (ref. 10).

Figure 3(a) gives fractional coverages by cesium of the polycrystalline tungsten surface. Initially the coverage drops off nearly exponentially with system temperatures; then it falls more and more rapidly with increasing temperature. Unfortunately only the high coverages here correspond to experimental data; the lower parts of these curves



(a) Equilibrium. (b) With elevated electron temperatures.

Figure 3. - Fractional coverages of plane polycrystalline tungsten surfaces (φ = 4.59 V) by cesium from plasmas (Saha).

depend on extrapolations using the correlation of reference 11.

Figure 4(a) indicates that work functions climb steeply with temperature initially, then level toward 4.59 volts. Below the work functions lie the plasma electron potentials relative to the emitter Fermi levels. Reference 3 presents the equation for these equilibrium plasma potentials:

$$\varphi_{oo} = \frac{T_E}{10^3}\left(0.1293 \ln \frac{T_{eP}}{10^3} - 0.08617 \frac{N_{eP}}{10^{12}} + 1.624\right) \tag{9}$$

The work function minus the plasma potential equals the overall sheath voltage plus the depression of the work function caused by the sheath field. This brings back the sheath-drop question of figure 1. Why do equilibrium sheath voltages for a constant work function drop steadily as temperatures rise while those for cesium on tungsten go through maximums? First, these sheaths build primarily with emission - the electron sheaths with emitted electrons, the positive-ion sheaths with emitted ions (refs. 1 to 3).

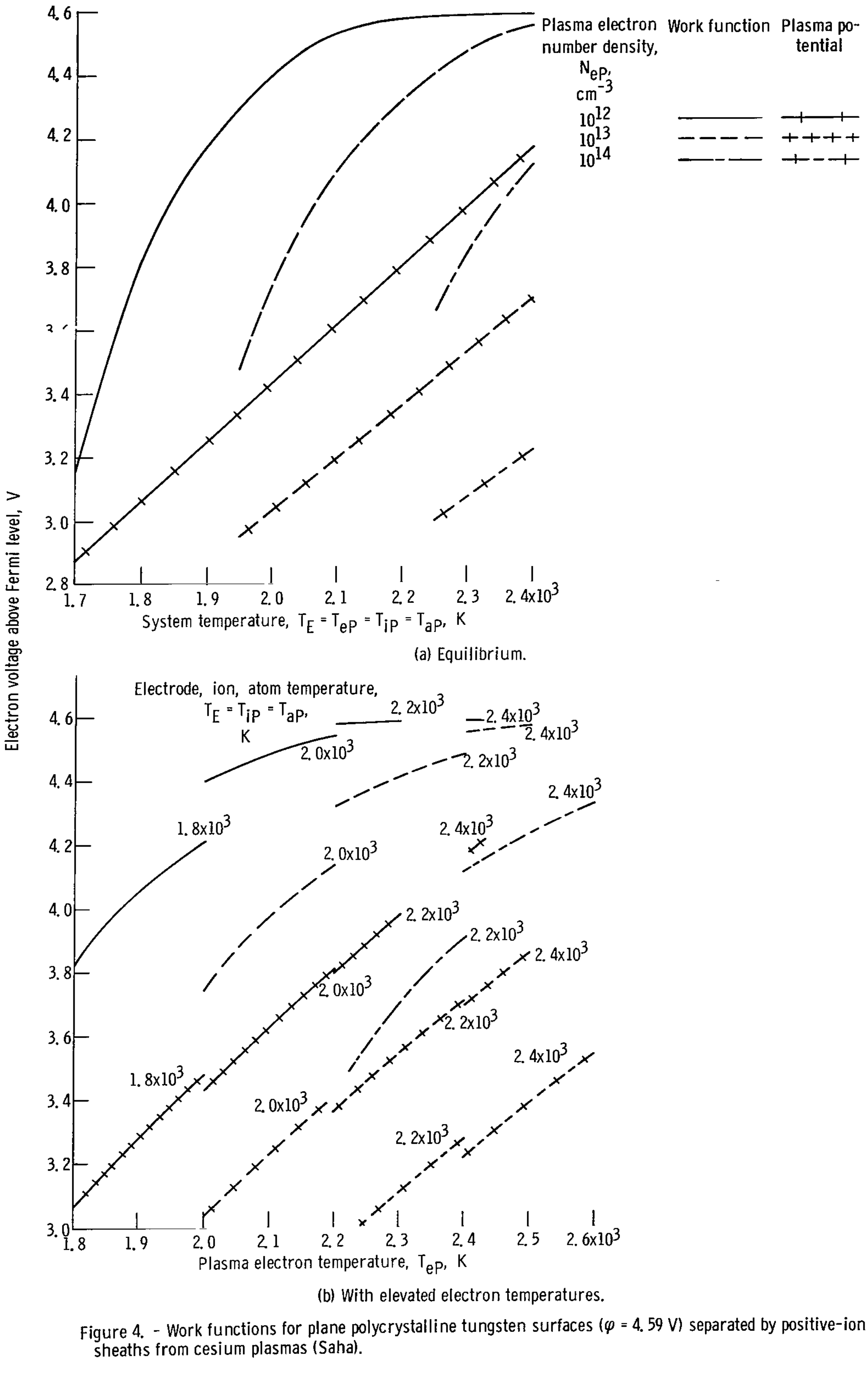


Figure 4. - Work functions for plane polycrystalline tungsten surfaces (φ = 4.59 V) separated by positive-ion sheaths from cesium plasmas (Saha).

Second, ion emission grows greater with higher cesium arrival and work functions and with lower electrode temperatures (ref. 8):

$$\frac{N_{iE}}{N_{aE}} = \frac{\exp\left[\frac{e(\varphi - I)}{\kappa T_E}\right]}{2} \tag{10}$$

But figures 2(a) and 4(a) show that small work functions hold ion production down while cesium arrivals are high and temperatures low. Then when work functions are high, low cesium arrivals and high temperatures drive the ion yield downward. As a result, sheath voltages pass through maximums where conditions are optimum for making and trapping ions.

Figures 1(b), 2(b), 3(b), 4(b), and 5 present results for near-equilibrium positive-ion sheaths. Here the plasma electron temperature ranges up to 200 K higher than that of the rest of the system. Yet for parts (b) of the figures the general comments for the (a) parts still apply. Now however the temperature of the emitter, ions, and atoms remains constant at the initial value for each curve. The trends of parts (b) derive primarily from the decrease in cesium arrivals at the electrode as the plasma electron temperature rises (fig. 2(b)). Because the plasma has a constant ionic concentration, higher electron temperatures require fewer neutrals to maintain the fixed number of ions (ref. 5); this causes the lower cesium arrival rate.

As references 1 to 3 show, the plasma potentials for these positive-ion emission sheaths differ for equilibria and near equilibria. Equation (9) applies to equilibrium, and the following expression gives plasma potentials relative to emitter Fermi levels for near-equilibrium positive-ion sheaths:

$$\varphi_o = \frac{T_E}{10^3}\left(0.1293 \ln \frac{T_{eP}}{10^3} - 0.08617 \frac{N_{eP}}{10^{12}} + 1.624\right) + I\left(1 - \frac{T_E}{T_{eP}}\right) \tag{11}$$

Values from equation (11) appear in figure 4(b).

Figure 5 also presents a distinct difference between the equilibrium and near-equilibrium positive-ion sheaths. Equilibria produce no net fluxes of particles, but net current densities climb abruptly from zero as the plasma electrons grow hotter than the rest of the system. After this sharp rise the curves seem to approach exponentials. Because the plasma electron temperature rises above that of the other particles and the electrode, these net currents flow from rather than to the plasma.

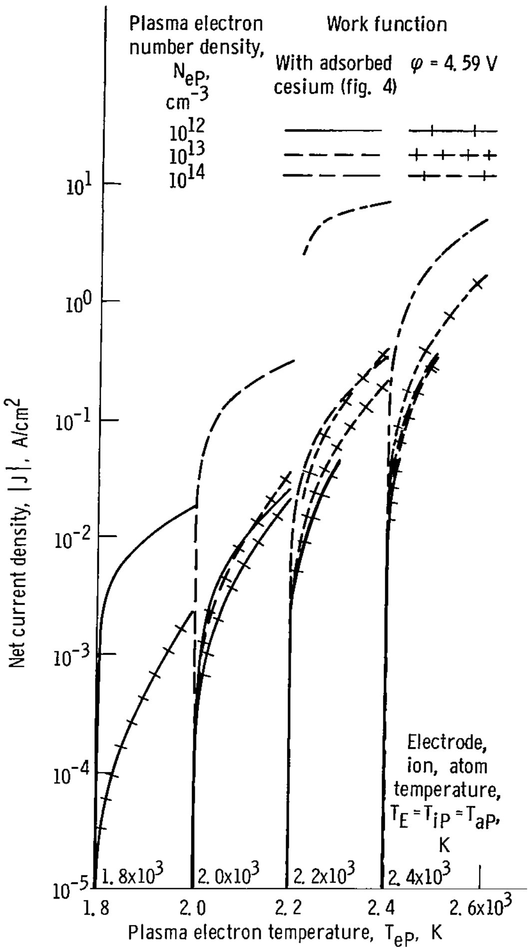


Figure 5. - Near-equilibrium currents through plane positive-ion sheaths separating polycrystalline tungsten surfaces (φ = 4.59 V) from cesium plasmas (Saha) with elevated electron temperatures.

CONCLUDING REMARKS

This study indicates effects of positive-ion sheaths on total cesium arrivals, surface coverages, and work functions of polycrystalline tungsten emitters. The results come from equilibria and systems with elevated plasma electron temperatures. Thus the present work parallels reference 1. That investigation, however, uses parametric work functions. In these calculations work functions vary below the 4.59-volt value of the bare electrode depending on the amount of adsorbed cesium. This difference allows an evaluation of the influence of work functions on sheath structures. For comparison, data computed with a constant work function of 4.59 volts also appear here.

The results of the present study verify the strong effects of ionic arrivals on properties of electrodes with positive-ion sheaths in cesium plasmas (refs. 1, 2, 3, 10, 17, and 18). For cesium diodes the implications of this phenomenon are obvious. Positive-ion sheaths increase electron emission by reducing effective work functions with sheath fields and cesium adsorption. Proper selection of conditions can build positive-ion sheaths that produce more power. But understanding and controlling the internal mechanisms of the diode depend on knowing the characteristics of the emitter. And a safe assumption at this point is that emitter properties have never been adequately determined for an efficiently operating thermionic diode (ref. 10). This state of ignorance persists both experimentally and theoretically.

Lewis Research Center.
National Aeronautics and Space Administration,
Cleveland, Ohio, March 20, 1968,
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