GPO PRICE $ _____

OTS PRICE(S) $ _____

Hard copy (HC) 1.00

Microfiche (MF) .50

Code 1

CR 60197

N65-15141

pp 9

Cat-25

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EMITTER SHEATH POLARITY IN PLASMA DIODES*

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Abstract

A phenomenological macroscopic model has been used to investigate the criteria used to determine the sign (polarity) of the emitter sheath in a broad-spaced plasma diode. It is shown that the ratio of electron emission current to ion emission current does not uniquely determine the emitter sheath sign. The net volume ionization and/or recombination and the electron plasma temperature are also shown to be important. No specific mechanism for volume ionization is assumed; both the net volume ionization and the electron temperature are treated as unknown parameters. Some numerical results obtained from this model are presented.

Introduction

The criteria presently used for determining the sign of the emitter sheath in both close-spaced and broad-spaced cesium plasma diodes are

$$I_s/I_{pE} > 491 = \text{electron rich (negative) emitter sheath,}$$

$$I_s/I_{pE} < 491 = \text{ion rich (positive) emitter sheath,}$$

where I_s is the electron emission current (as given by the Richardson equation) and I_{pE} is the ion current from the emitter. The applicability of this criteria to a close-spaced diode, where there are no interactions in the interelectrode space, cannot be questioned. In a broad-spaced diode, however, there are interactions in the interelectrode space and these interactions give rise to volume ionization and/or recombination. Since the presence of volume ionization in the interelectrode space of a plasma diode modifies the potential distribution, it must also enter into the determination of the emitter sheath sign. The criteria stated above, however, do not take into account such effects.

A phenomenological macroscopic model has been used to determine the correct criteria when interactions exist in the interelectrode space. Specifically, this model applies to a broad-spaced plasma diode where the spacing is many times the mean free path--i.e., to the case where a plasma, characterized by its own variables, is formed in the interelectrode space. No specific mechanism for volume ionization and/or recombination is assumed; both the net volume ionization and the plasma electron temperature are treated as unknown parameters. Plasma resistivity has been neglected. In this paper the equations that describe this model will be presented and the assumptions that were made will be discussed. Numerical techniques developed for the solution of these equations will not be covered; but some initial results will be presented.

* This research was supported by NASA Contract NSG-316 to the Institute for Direct Energy Conversion, Towne School of Civil and Mechanical Engineering, University of Pennsylvania.

Theoretical Model

Let I_s denote the electron emission current from the emitter surface. This current can be calculated from the Richardson equation if the concept of a work function is introduced. Since no current-voltage characteristics will be considered in this work, it is never necessary to introduce the concept of a work function. Instead, it is more desirable to work directly in terms of the electron emission current I_s. Let I_{so} be the electron emission current from the emitter surface when the emitter sheath potential vanishes. The motive diagram for this case is shown in Figure 1.

Using these definitions, the general criteria for determining the sign of the emitter sheath can be written as

$I_s > I_{so}$ = electron rich (negative) emitter sheath,

$I_s < I_{so}$ = ion rich (positive) emitter sheath.

These criteria are valid for all operating regimes in both close- and broad-spaced plasma diodes. For a close-spaced diode (no interactions in the interelectrode space), using the concept of charge neutrality it is easy to obtain the well known result*

$$I_{so} = \sqrt{m_p / m_e}\ I_{pE} = 491\ I_{pE}.$$

Using this, these general criteria reduce to the criteria stated in the preceding section.

Whenever interactions are present, I_{so} cannot be written down so easily. Interactions give rise to electron and ion currents returning from the plasma to the emitter surface; thus I_{so} must be a function of such currents. Since the calculation of these reverse currents requires a specific model, a phenomenological macroscopic model was used to determine the values of I_{so} for a broad-spaced plasma diode. In order that this model remain as general as possible, the electron temperature V_{Te} and the net volume ionization and/or recombination A_{DE} were chosen to be unknown parameters. Thus no specific ionization rates were assumed.

The basic assumptions used in this model are:

1. The temperature of the collector is low so that electron and ion generation at the collector are negligible.

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*It is important to emphasize that this result is independent of the question of the validity of the Saha-Langmuir equation since only the concept of charge neutrality was utilized in the derivation. The Saha-Langmuir equation enters only if one attempts to calculate I_{pE} in terms of I_s (or the emitter work function).

2. The Saha-Langmuir equation is a valid representation of ion generation at the the emitter surface. This equation, however, has been rewritten so as to use the electron emission current I_{so} explicitly . This means that the concept of an emitter work function is never explicitly introduced.

3. The plasma in the interelectrode space is uniform with the ion density equal to the electron density throughout.

4. Maxwellian distributions of electrons and ions exist in the plasma; the corresponding electron and gas temperatures, however, need not be equal.

5. Plasma resistance has been neglected.

6. Extraneous losses, such as thermal radiation from the plasma to the surroundings, loss of electrons, ions, and atoms from the interelectrode space are neglected.

7. Only two species of cesium are considered to exist in the plasma-atoms and ions. No provisions are presently made for the possible existence of excited atoms and/or molecules.

Using these assumptions, a set of six simultaneous equations has been formulated to describe the condition when the emitter sheath vanishes. Although a detailed derivation of this set of six equations will not be presented here, a brief discussion of each equation follows:

For <u>the current balance at the emitter surface</u>, the net current I is the result of four groups of charge carriers: (1) saturation current from the emitter I_{so}; (2) ion current from the emitter I_{pE}; (3) electrons from the plasma (reverse electron current) I_{ep}; and (4) ions from the plasma (reverse ion current) I_p.

Thus

$$I = I_{so} - I_{pE} + I_p - I\,ep \,. \tag{1}$$

For the <u>current balance at the collector surface</u>, the net current I is the result of only two groups of charge carriers: (1) electrons from the plasma $I_{ep}\exp(-V_{SC}/V_{Te})$; and (2) ions from the plasma I_p, where V_{Te} denotes the electron plasma temperature. The collector sheath is always assumed to be positive in this model. Thus

$$I = I_{ep}\exp(V_{SC}/V_{Te}) - I_p \,. \tag{2}$$

The equation for the <u>ion balance across the plasma</u> is

$$I_{pE} + A_{DE} = 2I_p \,. \tag{3}$$

where A_{DE} is the net volume ionization and/or recombination in amps/cm^2.

The equation for the <u>ion production at the emitter is</u>

$$I_{pE} = I_a / [1 + 2I_{so}\exp(V_i/V_{TE})\,AT_E^2] \tag{4}$$

where

I_a = arrival rate of atoms and ions from the plasma,

V_i = ionization potential of cesium,

V_{TE} = emitter temperature (ev),

A = thermionic emission constant (120 amps/cm^2).

This is the Saha-Langmuir equation, rederived in a manner such that the concept of an emitter work function is never explicitly introduced.

The equation for the <u>charge density balance in the plasma</u> is

$$I_{ep}\sqrt{m_e/V_{Te}} = I_p\sqrt{m_p/V_G} \tag{5}$$

where V_G denotes the gas temperature (ev).

The equation for the <u>energy balance</u> for the plasma is

$$2\,I_{so}\,(V_{TE} - V_{TE}) + 2\,I_a\,(V_{TE} + V_{TC} - 2\,V_G) \tag{6}$$

$$- A_{DE}\,(V_i + 2\,V_{Te}) - (I + I_p)\,V_{SC} = 0,$$

where V_{TC} is the collector temperature (ev). Although the approach used to obtain this equation is similar to that employed in Reference 1, the reference points and grouping of terms used are fundamentally and significantly different. This equation expresses the fact that the net energy flowing across an imaginary surface immediately outside the emitter must equal the net energy flowing across a similar imaginary surface immediately outside the collector when the same potential reference points are used for both imaginary surfaces. Since only ions and atoms are considered to be crossing these imaginary surfaces, the possible presence of excited atoms and/or molecules has been neglected.

Special numerical procedures have been developed to solve these six simultaneous non-linear coupled equations without introducing any additional numberical approximations. The input variables are T_E, T_C, T_G, and I_a. For each value of A_{DE} and V_{Te} chosen, a numerical search is carried out to find a solution of these equations in terms of I_{so}. Such a solution may or may not be found. If a solution is found, it means that for the values of T_E, T_C, T_G, I_a, A_{DE} and V_{Te} chosen, a zero emitter sheath solution exists for the value of I_{so} found. If no solution is found, no zero emitter sheath can exist for the conditions chosen.

Results

Since A_{DE} and V_{Te} are treated as independent variables, the solutions found for each set of values of T_E, T_C, T_G, and I_a will be a family of curves on a plot of I_s versus A_{DE}. Each curve in this family can be labeled with a value of V_{Te}. Physical conditions on this set of equations (e.g., $I_p \geq 0$, etc.) restrict this family of curves to a specific region of the I_s - A_{DE} plane.

As a first step in the solution of this set of equations, it is convenient to find the envelope of this family of curves. An analytical procedure has been found for solving these equations for this envelope. Figure 2 shows a typical for $0 \geq V_{Te} \geq \infty$ with the various significant features labeled. The two lines extending to the right meet at infinity. The limits $0 \geq V_{Te} \geq \infty$ arise from the use of V_{Te} as a mathematical parameter in the analytical solution. All solutions for I_{so} as a function of A_{DE} and V_{Te} lie within the boundaries of this envelope.

Physically, it is clear that $V_{Te} \geq V_G$. The inclusion of this fact, however, is not simple. A solution for the envelope with the restriction $V_{Te} \geq V_G$ yields a portion of the envelope in Figure 2; but this portion is not closed. To find the full envelope it is necessary to solve for the solution for $V_{Te} = V_G$. This has been done and the results are shown in Figure 3.

Any broad-spaced plasma diode operating above the top curve in Figure 3 necessarily possesses an electron rich (negative) emitter sheath. Any broad-spaced plasma diode operating below the bottom curve in Figure 3 necessarily possesses an ion rich (positive) emitter sheath. From this Figure it is clear that an increase in the net volume ionization with all other parameters constant can cause the operation of such a plasma diode to go from an electron rich to an ion rich emitter sheath.

For plasma diodes operating in the region between the two curves in Figure 3, it is impossible to state whether the emitter sheath is positive or negative without having more information. First, the entire parametric family of curves ($\infty \geq V_{Te} \geq V_G$) would be needed for the region bounded by this envelope. From this family the specific solution that relates A_{DE} to V_{Te} must then be defined. Only after this precise curve is known can conclusions be drawn about emitter sheaths for plasma diodes operating in the region between the two curves in Figure 3. Further theoretical research on the behavior of the solutions in this region is currently in progress.

Summary

A phenomenological macroscopic model has been used to investigate the criteria used to determine the sign of the emitter sheath in a broad-spaced plasma diode. Results are presented that clearly show the effects of volume ionization and/or recombination. Since the electron temperature and the net volume ionization are both treated as independent variables, these results are a parametric family of curves. The envelope of this family is bounded in the $I_s - A_{DE}$ Plane. It is anticipated that these results will be useful in understanding the current voltage characteristics of broad-spaced plasma diodes.

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MOTIVE DIAGRAM

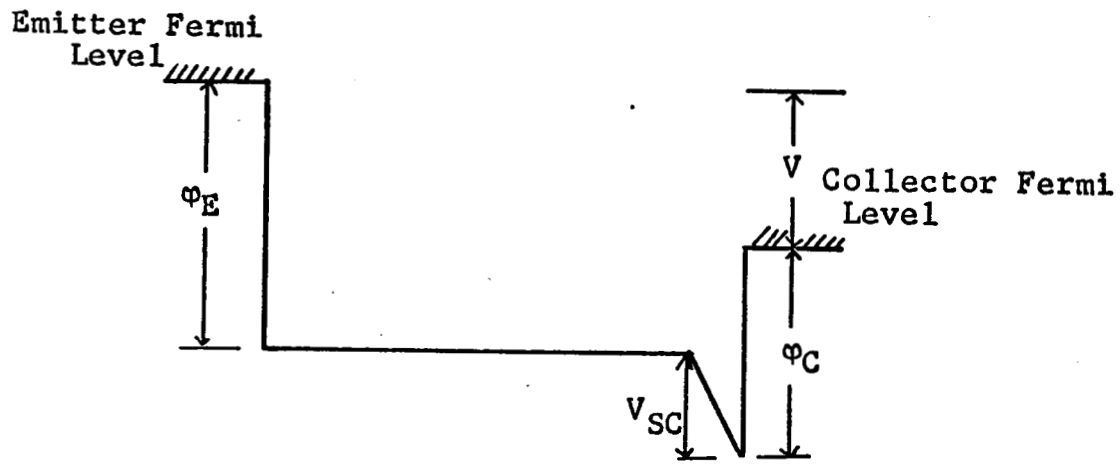

Figure 1. Motive diagram for a zero emitter sheath.

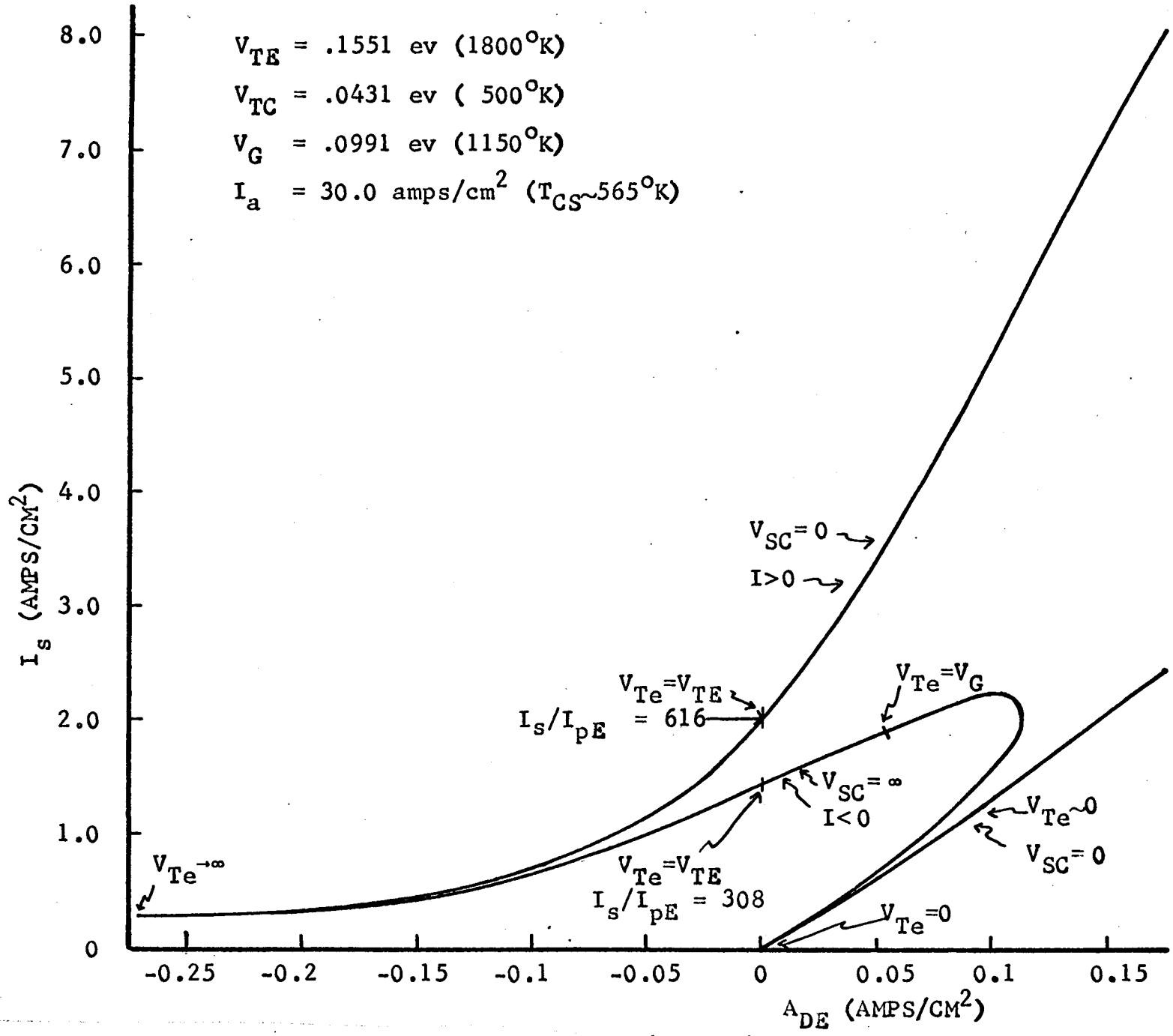

Figure 2. Envelope of zero emitter sheath solutions for $0 \leq V_{Te} \leq \infty$.

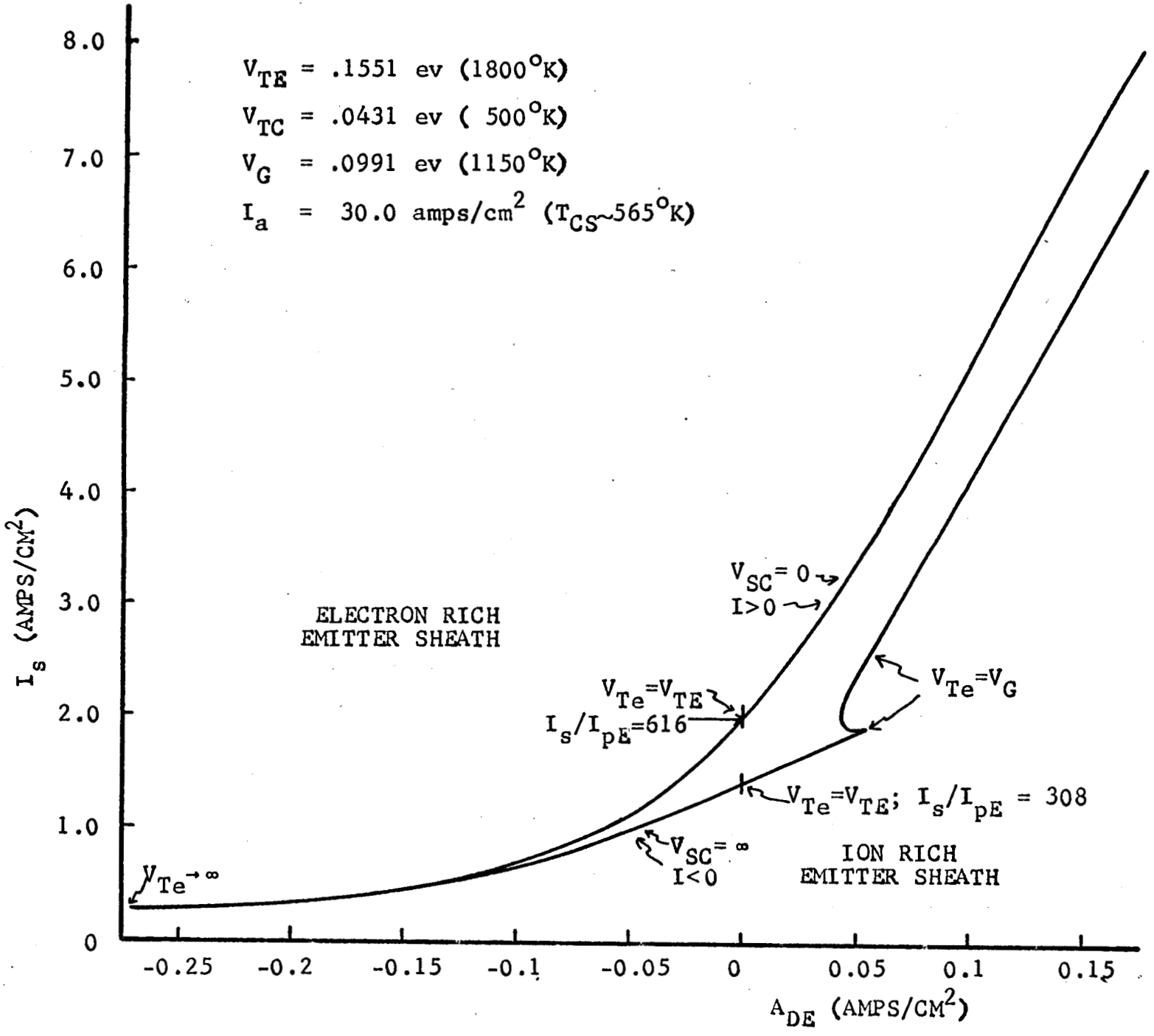

Figure 3. Envelope of zero emitter sheath solutions for $V_G \leq V_{Te} \leq \infty$.