MASTER

APPLICATION OF MICROFABRICATION TECHNOLOGY
TO THERMIONIC ENERGY CONVERSION

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ABSTRACT

In a theoretical and experimental program to evaluate those areas where three-dimensional microfabrication techniques could be important for improving methods of thermionic energy conversion, effort in the first reporting period has been directed toward a theoretical study of microstructures of electrodes for thermionic energy converters. The properties of a cesiated tungsten thermionic energy converter were analyzed with electrode temperatures compatible with a flame-generated heat source ($T_c = 1650^\circ\text{K}$ and $T_a = 700^\circ\text{K}$), in order to estimate the efficiency, power^c production, and appropriate electrode spacing^a for microfabricated devices. The analysis yielded a maximum efficiency of sixteen percent and corresponding electrical power of 11 W/cm^2 , requiring an emission current of 18 A/cm^2 . The study revealed that to attain these parameters, electrode spacing must be approximately $1 \mu\text{m}$, and that such a close-spaced diode with cesiated tungsten electrodes would operate approximately as a vacuum diode. That is, the principal function of the cesium would be to control the work function of the electrode surfaces. Operating at the point of peak efficiency, little space-charge limitation of the emission and little plasma resistance would be produced, because the atom/atom and electron/atom mean free paths would be larger than the interelectrode space.

I INTRODUCTION

This is the first progress report in a theoretical and experimental program to evaluate those areas where three-dimensional microfabrication techniques could be important to improving methods of thermionic energy conversion. SRI International (SRI) is conducting the program for the Division of Fossil Fuel Utilization, Department of Energy (DOE) under Contract No. DE-AC02-79ET15423.

The scope of work encompasses a three year level-of-effort program to evaluate the significance of application of ultramicrofabrication techniques to thermionic energy conversion. To this end, the following specific steps will be attempted:

- Step 1: Prepare structured electrodes
- Step 2: Build and evaluate a submicron close-spaced diode
- Step 3: Study field ion injection for space-charge neutralization
- Step 4: Conduct microfabrication service for programs in the thermionic energy conversion field.

The first year's effort is directed mainly toward Step 1, with some effort applied to Step 2. This report covers the period 1 May 1979 through 31 October 1979.

II PROGRESS DURING THE REPORTING PERIOD

In the period covered by this report, the effort has been directed toward a theoretical study of microstructures of electrodes for thermionic energy converters (Task 1 in the Statement of Work). The properties of a cesiated tungsten thermionic energy converter were analyzed with electrode temperatures compatible with a flame-generated heat source. The purpose of this analysis was to estimate the efficiency, power production, and appropriate electrode spacing for microfabricated devices. The analysis yielded a maximum efficiency of 16 percent at which the electrical power was about 11 W/cm^2 , requiring an emission current of about 18 A/cm^2 . We determined that to attain these parameters, the electrode spacing must be approximately $1 \text{ }\mu\text{m}$.

Two significant aspects of a microstructured diode have emerged from the theoretical analysis. First, with a $1 \text{ }\mu\text{m}$ spacing and with a cesium pressure needed to attain the desired work function of about 2.4 V, the atom/atom mean free path is greater than the electrode spacing. The same is true for the electron/atom mean free path. For these reasons, we expect

the internal voltage drop caused by plasma resistance to be very small compared to the diode voltage. The second significant aspect can be related to space-charge conditions. Because of the small spacing, cesium ions are not needed in the gap for space-charge neutralization. In other words, the saturated thermionic emission current is not space-charge limited to any significant extent. Thus, by virtue of these two features of close electrode spacing, the cesium is required only to control the emitter work function; it is relieved of its other role of providing space-charge neutralization in the gap, where it also contributed a negative effect of plasma resistance.

The following section discusses the theoretical analysis that led to the conclusions that have been summarized above. The next report will describe progress on choosing electrode geometries and methods of fabrication to produce a diode with a 1 μm interelectrode gap.

III DISCUSSION

The theoretical analysis was designed to yield a quantitative evaluation of the operating parameters that might be assigned as design goals for a microfabricated diode. The analysis was performed in two steps. In the first step we determined the desirable electrical parameters for a diode; in the second step, we determined the gap spacing that would be needed to ensure the attainment of those parameters.

We chose to analyze a diode in which both the emitter and collector were cesiated tungsten electrodes. Because data are available for cesiated tungsten over a wide range of operating conditions; cesiated tungsten has a very low evaporation rate; and SRI is experienced in tungsten thin-film technology.

Low evaporation rate is an important criterion for thermionic diodes, where long operating lifetimes are difficult to attain. Shorting between the electrodes is relatively common failure mode that results from the migration of evaporated materials. Because this problem would be particularly enhanced with ultra-closely-spaced diodes, we decided to analyze the very low evaporation rate material. Choosing the same material for both electrodes has the advantage of preserving the integrity of the initial characteristics over long operating lifetimes: The coating of one electrode by evaporant material from the other electrode is much less likely to effect its characteristics when the materials are the same.

The other initial conditions selected for this analysis are the electrode operating temperatures. We used an anode temperature $T_a = 700^\circ\text{K}$ and a cathode temperature $T_c = 1650^\circ\text{K}$. These temperatures are compatible with a flame-fired converter^C diode clad with a silicon carbide protective shield.

The emission current is one of the most important parameters that governs the operation of a thermionic diode. If electron reflection at the solid vacuum interface is neglected, the governing relation is the Richardson-Dushman equation, given by

$$J_s = 120 T^2 \exp(-e\phi/kT)$$

where J_s is the saturated emission current density, T is the absolute temperature of the solid, e is the electronic charge, k is Boltzmann's constant, and ϕ is the effective work function.

In a converter analysis, both the cathode emission and the back emission from the anode must generally be considered. Although the anode temperature is much lower than the cathode temperature, its emission can be significant in cases where the anode work function is very low. This is not the case, however, in this analysis, where we have chosen a cesiated tungsten anode. At a temperature of 700°K, the anode surface is effectively coated with cesium and exhibits the work function of cesium, or $\phi_a = 1.7$ V. The saturated anode emission is thus $J_a = 34 \mu\text{A}/\text{cm}^2$, which as demonstrated below, is a negligible amount. At the chosen operating temperature, the saturated cathode emission is

$$J_{cs} = 3.267 \times 10^8 \exp(-7.032 \phi_c)$$

The efficiency η of an idealized converter is defined as the electrical power output divided by the total thermal power that must be delivered to the converter. The total thermal power includes cathode heat losses caused by electron emission cooling, radiation, and heat conduction loss through the electrical connection (Houston and Webster, 1962). When these factors are considered, the efficiency is given by:

$$\eta = \frac{J_c (\phi_c - \phi_a - V_w)}{J_c (\phi_c + 2kT_c/e) + R + H_w}$$

where R is the radiation heat loss, H_w is the heat conduction through the electrical lead, and V_w is the voltage drop in the electrical lead. If radiation from the lead is neglected, and the electrical and heat conductivities of the lead are assumed to be related by the Lorenz number L , the voltage drop V_w and the heat conduction per unit cathode area H_w of the optimum lead are given by:

$$V_w = [L\eta (T_c^2 - T_a^2)/(2 - \eta)]^{1/2}$$

$$H_w = J_c V_w (1 - \eta)/\eta$$

where L is 2.45×10^{-8} W-ohm/deg² and η is the converter efficiency.

The four equations above were solved simultaneously with the following input parameters: $T_c = 1650^\circ\text{K}$, $T_a = 700^\circ\text{K}$, and $\phi_a = 1.7\text{V}$. Additionally we expressed the radiation loss as $R = \epsilon R_{bb}$, where R_{bb} is the black body radiation for the chosen cathode temperature ($R_{bb} = 5.672 \times 10^{-12} T_c^4$ in W/cm^2). We used $\epsilon = 0.3$, being representative of a reasonably obtainable surface emissivity. The solution of converter efficiency as a function of cathode work function is given in Figure 1. It is seen that the peak efficiency of 16.3 percent occurs at a cathode work function of 2.38 V. The efficiency is fairly strongly peaked, being small above 3 V and below 1.8 V.

The electrical power output, the thermal conduction to the connecting lead, and the total thermal power were also obtained in the solution and are plotted in Figure 2. The radiation loss is also shown as the dashed line. The point of maximum efficiency is shown in the figure. At this point the electrical power output is about 11 W/cm^2 and the total thermal power required is 65 W/cm^2 . The saturated emission current at maximum efficiency is about 18 A/cm^2 . The results of this calculation show that the electrical power peaks at a considerably lower work function than the position of maximum electrical efficiency. At the maximum power point, the required cathode work function is very low and the thermal power is exceptionally high, as is the required saturated current density. It is quite conceivable that in this converter design the attainable electrical power output will be limited by the capability for supplying thermal energy to the cathode.

The second step of the analysis was to examine the conditions for attaining the desired emission current in the converter. As shown earlier, the anode emission in our design is negligible, so it is not necessary to reverse bias the converter to suppress anode emission. Also, as will be shown later, we expect negligible plasma resistivity because of the closely-spaced gap. Therefore we can express the converter voltage V as the difference between the work functions of the electrodes, $\phi_c - \phi_a$, and can now examine Child's law for space-charge limited emission to determine gap spacing required to allow the saturated thermionic emission to pass without being space-charge limited. Child's law is given by:

$$J = 233.45 V^{1.5} / d^2$$

where J is in A/cm^2 , V is in Volts, and d is in μm . This relationship is plotted in Figure 3, that expresses the electrode gap, d , as a function of cathode work function ϕ_c . At the maximum efficiency point, an electrode spacing of $2.7 \mu\text{m}$ or less would be sufficient, whereas at the maximum power point a submicron electrode gap would be required to permit the saturated current to flow.

FIGURE 1 EFFICIENCY OF THE IDEALIZED CONVERTER

FIGURE 2 ELECTRICAL POWER OUTPUT AND THERMAL POWER DISSIPATION OF THE IDEALIZED CONVERTER

FIGURE 3 INTERELECTRODE SPACING OF THE IDEALIZED CONVERTER

Because potential differences in a vacuum converter are relatively small, electron thermal velocities cannot be neglected in any analysis of electron space charge; thus, Child's law gives only approximate results. Langmuir (1923) has calculated the potential distribution in a planar diode assuming the electrons issue from the cathode with a Maxwellian distribution of velocity. The current-voltage characteristics of the diode can be expressed in terms of the space-charge parameter R' which is defined by the equation

$$R' = 8424 J_{cs} d^2 / T_c^{3/2},$$

where J_{cs} is in A/cm^2 and d is in μm (Houston and Webster, 1962).

When $R' = 0$, space charge effects are negligible. Larger values of R' are indicative of increasing space-charge effects that reduce the emission current below the saturation value. We have plotted in Figure 3 a curve for the value $R' = 5$; this corresponds to an emission about 75 percent of the saturation value when the diode internal voltage is 0. Thus in the figure, diode spacings below the curve are sufficient to provide at least 75 percent of saturated emission current. At the peak efficiency point ($\phi_c = 2.38$ V), values below $1.5 \mu m$ are acceptable. Based upon these results, we chose a nominal gap spacing of $1 \mu m$ as a design target.

IV PERCENTAGE OF TIME SPENT ON THIS EFFORT

During this reporting period, the principal investigator spent approximately 8 percent of his working time on this program. During the remainder of the contract, the principal investigator will devote approximately 600 hours of his time.

REFERENCES

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