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UCRL 6809

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EMISSION CHARACTERISTICS
OF TANTALUM, TUNGSTEN, RHENIUM
AND IRIDIUM IN PLASMA DIODES

Livermore, California

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UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Livermore, California

Contract No. W-7405-eng-48

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April 2, 1962

(Presented at the 22nd Conference on
Physical Electronics, March 21-23, (1962)

Facsimile Price \$ 1.60
Microfilm Price \$.80

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

This paper was submitted for publication
in the open literature at least 6 months
prior to the issuance date of this Micro-
card. Since the U.S.A.E.C. has no evi-
dence that it has been published, the pa-
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Abstract

Experimental determinations of the ionic and electronic emission characteristics of tantalum, tungsten, rhenium, and iridium cathodes in vapor thermionic convertors are compared. It is shown that tantalum provides superior thermal ionization qualities at high pressure compared with tungsten, rhenium, and iridium. High electronic current densities may be obtained from cesium on rhenium and cesium on iridium at much lower cesium vapor pressures than for tantalum or tungsten.

Introduction

The intention of this report is to compare experimental results obtained from vapor thermionic convertors which had high bare surface work functions with those of the more commonly used materials, i. e., Re and Ir vs Ta and W.

Equipment

Identical geometry was used in making these comparisons. It consisted of a guard ring system which had a 20-mil-diameter cathode placed coaxially in a 40-mil-diameter bore. It is shown schematically in Fig. 1. The tubes were baked in an oven at 450°C during evacuation and the secondary electrodes were heated to a dull red by electron bombardment or induction heating until the base pressure of the pumping system, 10^{-8} mm Hg, was reattained. Cathodes were aged with occasional flashings until reproducible saturated emission curves were obtained in vacuum. Cesium was then introduced into the tube.

The ambient temperature of the cesium was measured with a thermocouple which was spot welded to a tungsten pin imbedded in the bottom of the tube as shown in Fig. 1. Cesium pressure and atom flux densities corres-

ponding to these temperatures were obtained from the Smithsonian Physical Tables.¹ Cathode temperatures were determined by optical pyrometry; emissivity and glass wall corrections were added. The cathode was heated directly with a regulated dc power supply which was pulsed off for about 8 milliseconds per second. All data were recorded when no power was being applied to the cathode. Guard ring potentials were maintained at anode potential with a dc bias, while anode potential was controlled by resistive loading only. Anode temperature was not controlled, but was monitored with a Pt-Pt-Rh thermocouple spot welded to the anode.

Results

Plots of self-developed output current density vs cathode-anode terminal voltage for different cathode materials are shown in Fig. 2. The initial bare surface work functions, ϕ_b 's, and the corresponding " A_r " values as determined from Richardson plots are noted. Cathode temperatures for these data were about equal.

The plots of the tantalum and tungsten data essentially duplicate what has been done before. However, the rhenium and iridium cathodes demonstrate qualities not previously reported.

The iridium cathode adsorbed cesium so strongly that it attained emitted current densities of the order of amperes per square centimeter at a cesium pressure of 160μ Hg.

Further, at low pressure, the current density vs voltage profiles of the iridium tube certainly indicate the lack of proper space-charge neutralization. This phenomenon has not been observed in well outgassed systems for the other materials at corresponding pressures and cathode temperatures. When the cesium pressure was increased to about 10μ Hg, the system became reasonably well neutralized and the normal type of current density vs voltage profile was obtained. Further increase in pressure caused the profiles to become rounded in a manner typical of those of other materials at much higher pressures. Reduction of pressure to low levels produced the same distorted profiles.

Scattering cross sections for electrons with energies less than 0.5 volt are not well known. If a cross section of 25 angstroms squared is assumed, the mean free path of an electron in cesium gas at 160μ Hg is about 0.1 cm, while the average interelectrode distance was 2.54×10^{-2} cm.

Since the same rounded type of voltage versus current density profile was obtained at a pressure an order of magnitude less than for Ta or W, and the mean free path was about four times the interelectrode distance, it appears likely that inadequate space charge neutralization rather than scattering was the primary inhibitor of further increased current under these conditions.

Langmuir has shown that under conditions of equilibrium, the Saha-Langmuir equation for thermal ionization may be applied to a surface subject to cesium adsorption.² This equation expresses the ratio of emitted cesium ions to emitted atoms as

$$\frac{\nu_i}{\nu_a} = \frac{1}{2} \exp \left[(\phi - I) \frac{e}{kT} - \ln \frac{j_p}{j_b} \right] \quad (1)$$

where j_p and j_b are the current densities at pressure and bare surface respectively and the remaining terms have their usual designations. The term $\ln(j_p/j_b)$ expresses the work function depression caused by cesium adsorption.

When the output voltage is at an optimum for power output, the surface potentials of the cathode and anode are about equal. This means that if the interelectrode plasma is properly neutralized, the emission is equivalent to zero field emission from the cathode and the term derived from the Richardson equation may be used. Profiles in which the output current density does not change as output voltage is increased from about zero to the break-off voltage provide a good measure of the current density at the optimum power output point. Current density values taken from the rounded profiles provide less accurate data, but have been included since they occur in a region of great interest.

This equation has been applied to plasma diode experimental results in order to get some notion of the thermal ionization characteristics, even though complete equilibrium may not exist in these systems. Reflection coefficients are assumed equal to zero.

At steady state $\nu_i + \nu_a = \mu_a$ where μ_a is the number of atoms/cm²-sec incident on the cathode surface.

From this

$$\nu_i = \left(\frac{\frac{\nu_i}{\nu_a}}{\frac{\nu_i}{\nu_a} + 1} \right) \mu_a. \quad (2)$$

Figure 3 shows the results obtained when experimentally determined output current density ratios are used in Eqs. (1) and (2). The numerical values used in these determinations were: ϕ_b and j_b obtained from a Richardson plot, $I = 3.89$ volts and a value of j_p taken at $V_p \approx 0.5$ volts as a function of pressure. Anode temperatures were about 700°K. The point of primary interest is that the tantalum surface continued to ionize efficiently at considerably higher pressure than the iridium and rhenium surfaces.

These phenomena suggest that a cathode composed of a material which combines work functions like those of tantalum and rhenium might offer superior qualities. The high work function crystal faces of the rhenium would adsorb cesium readily to provide good electron emission while the tantalum remained substantially bare and would provide positive ion emission. In other words, the high heat of adsorption of cesium on rhenium would cause the cesium to condense whereupon the mobility of the condensed cesium would allow migration to a tantalum crystal face where the heat of adsorption is less and the cesium could be emitted as an ion. Copious ion emission is then an inherent quality of the tantalum surface. Potential barriers which might prevent ion emission are, in principle, subject to elimination by other means.

It has been found that rhenium is a very tractable cathode material for thermionic convertor investigations. Figure 4 shows the profiles obtained with a rhenium cathode for four temperatures as cesium pressure was varied. The rhenium plot in Fig. 2 may also be added to these data.

Output current density for tantalum and tungsten cathodes at low cesium pressures is sometimes even less than the values obtained for saturated emission in vacuum. The rhenium cathode does not demonstrate this peculiarity, but offers a steady increase in output current density for each pressure step. The work function depression of the four materials at a common

temperature and of rhenium alone at five temperatures are shown versus pressure in Fig. 5.

Efficiencies greater than 15% are easily attained with rhenium cathodes. The best in these data was about 19% with a cathode temperature of 2440°K and a cesium pressure of 2900 μ Hg.

The superior characteristics of the rhenium cathodes are probably related to the high heat of adsorption and to its hexagonal close-packed crystal structure. The influence of these factors has not been fully investigated at this time.

Acknowledgment

I wish to thank Dr. Charles E. Williams for much aid and advice in the preparation of this report and also to thank Mr. Don Brown and Mr. Everett McKee for excellent cooperation in tube construction and processing.

References

* Work performed under the auspices of the United States Atomic Energy Commission.

¹ W. E. Forsythe, Smithsonian Physical Tables (Smithsonian Institute, Washington, D. C. 1956) Ninth Revised Edition.

² I. Langmuir, Phys. Rev. 44 423 (1933).

Figure Captions

Fig. 1. Schematic diagram of the experimental tubes used.

Fig. 2. Output current density j_p (amps/cm²) vs output voltage V_p for (a) tantalum cathode at 2110°K, (b) tungsten cathode at 2140°K, (c) rhenium cathode at 2140°K, and (d) iridium cathode at 2150°K.

Fig. 3. Emitted cesium ion current density (ions/cm² $\times$ sec) vs cesium pressure (μ Hg).

Fig. 4. Output current density j_p (amps/cm²) vs output volts V_p for rhenium cathode at (a) 2250°K, (b) 2350°K, (c) 2440°K, and (d) 2540°K.

Fig. 5. Work function depression $\Delta\phi$ (volts) vs cesium pressure (μ Hg).

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