The Thermionic Properties of Tantalum

ALVIN B. CARDWELL, *Department of Physics, University of Wisconsin*

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Tantalum was carefully outgassed and its photoelectric and thermionic properties simultaneously studied. As was shown in a previous paper, heating 1000 hours at temperatures up to 2200°K produced an *apparent stable condition* of the surface. Further heat treatment at temperatures up to 2500°K produced a *final stable condition*. The values obtained for the thermionic constants of the T^2 law are, when corrected for the Schottky effect, as follows: (1) For surface in *first apparent stable condition*, $b=52{,}532$°K and $h=4.53$ volts. (2) For surface in *final stable condition*, $b=47{,}560$°K, $h=4.10$ volts and $A=37.2$ amp./cm² degree². A comparison of these results with the previously published photoelectric data shows that the value of the photoelectric work function determined according to Fowler's method agrees with the value of the thermionic work function of the *same* surface regardless of whether the surface is thoroughly outgassed.

IT is evident from the theoretical work of Sommerfeld[1] that the photoelectric work function determined according to the method of Fowler[2] should be identical with the thermionic work function. Since Fowler's method does not give a value very different from that obtained by the extrapolation method, it may be said that, within the limits of experimental error, such a conclusion has been verified in the case of tungsten,[3] platinum,[4] molybdenum,[5] and palladium.[6] The present paper is a report, supplementing one already published by the writer,[7] of measurements on tantalum which further verify this theory.

Apparatus and Procedure

The apparatus used in the present work was the same as that schematically diagrammed and fully described in the previous article to which reference has already been made. The tube was specially designed for both photoelectric and thermionic observations, a guard ring being so placed that no correction was necessary for end losses. Thermionic currents were measured by a Leeds and Northrup galvanometer, the effective sensitivity of which could be varied over a wide range by means of a system of external shunts. The tantalum filaments, obtained from the Fansteel Company of North Chicago were made from a very pure sample of the metal.

Since simultaneous readings of the temperature and thermionic currents were taken, it was necessary to maintain the thermionic current at a constant value (to 0.2 percent) while each particular observation was being made. This was accomplished by using four thirty-volt banks of large new lead storage cells in parallel. This combination was connected in series with the filament and a variable low resistance which was shunted by a high resistance rheostat for fine adjustment.

Temperature measurements

Temperatures were determined by means of an optical pyrometer of the disappearing filament type focused on the filament through a very thin, optically flat quartz window. Condensation of tantalum onto this window during the intervals when observations were not being made was prevented by means of a magnetically controlled door over the opening in the receiving cylinder. The pyrometer was calibrated originally by Dr. M. J. Martin and Mr. C. K. Eckels. During the present work the author recalibrated the instrument by observations, through a quartz window of the same thickness as that used in the tube, on the gold point and palladium point. The two calibrations were in excellent agreement. Blackbody temperatures were corrected for the emissivity of tantalum according to the data of Mendenhall and Forsythe.[8]

Outgassing process

The outgassing process to which each sample was subjected varied slightly. Essentially, however, the process was briefly as follows: After the

[1] Sommerfeld, Zeits. f. Physik **47**, 1 (1928).
[2] Fowler, Phys. Rev. **38**, 45 (1931).
[3] Warner, Proc. Nat. Acad. Sci. **13**, 56 (1927).
[4] DuBridge, Phys. Rev. **31**, 236 (1928).
[5] Martin, Phys. Rev. **33**, 991 (1929).
[6] DuBridge and Roehr, Phys. Rev. **39**, 99 (1932).
[7] Cardwell, Phys. Rev. **38**, 2041 (1931).
[8] Mendenhall and Forsythe, Astrophys. J. **37**, 380 (1913).

installation of the sample, the entire tube and ionization gauge were baked at 500°C for twenty days. During the last fifteen days of this interval the filament was heated by a conduction current at temperatures which were slowly increased to 1700°K. At the end of this period the furnaces were removed and the filament further heated for 620 hours (a total heat treatment of 1100 hours) at temperatures which were finally increased to 2500°K (50 hours at this temperature). On several occasions the filament was flashed for five minutes at a temperature of 2700°K. After this strenuous heat treatment the pressures, measured by an ionization manometer, were from 2 to 8×10^{-8} mm of Hg.

Schottky effect

Unfortunately the filaments burned out before data on the Schottky effect were obtained. However, because of the geometry of the apparatus it is possible to make an approximate calculation of the correction which should be applied to b. Such a calculation yields a correction $\Delta b=195$.

Results

(1) Sample in first apparent stable condition

In the previous paper[7] attention was called to the fact that after 1000 hours of heat treatment at temperatures up to 2200°K the tantalum sample reached an apparently stable condition which could be changed only by heating to much higher temperatures. While the sample was in this condition, both photoelectric and thermionic measurements were made. The photoelectric curves and their analyses according to Fowler's method have already been published.[7] Fig. 1 of the present paper shows the logarithmic plot of thermionic data taken while the sample was in this condition. The slope of this curve, corrected for the Schottky effect, yields a value for b of 52,532°K, or 4.53 equivalent volts. This is in very good agreement with the corresponding photoelectric work function of 4.51 volts. (See previous paper.[7])

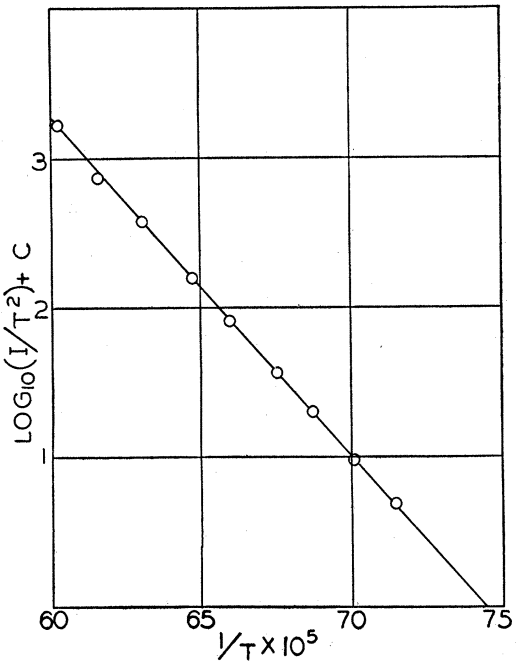

FIG. 1. Logarithmic plot of thermionic data for tantalum taken after 1000 hours of heat treatment at 2200°K.

(2) Sample in final stable condition

Fig. 2 is a sample curve showing the usual Richardson plot from data taken after the sample, as a result of heating to 2500°K or higher, had

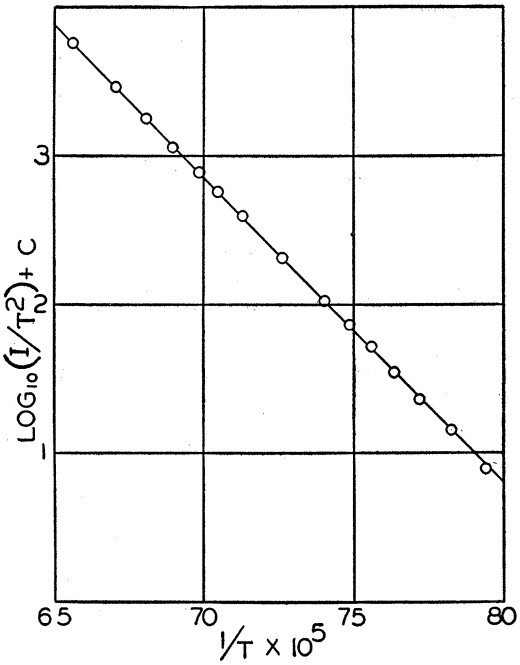

FIG. 2. Richardson plot of thermionic data on tantalum after continued heating at 2500°K.

reached what seemed to be its final stable condition. The slopes of fourteen such curves yield an average value for the constant b in Richardson's equation of 47,365°K. When this value has been corrected for the Schottky effect and 5.69 cm² used as the effective area of the emitting surface, the constants of the Richardson equation are:

$b=47{,}560°K$;
$h=bk/e=8.62\times10^{-5}b=4.10$ volts;
$A=37.2$ amperes/cm² degree² (average value for 14 curves).

By Fowler's method the photoelectric work function for the metal while in this final stable condition was found to be 4.13 volts at 273°K and 4.18 volts at 973°K. (See previous paper.[7])

Recently Becker and Brattain[9] criticized the indiscriminate use of the term "work function." They conclusively argued that the thermionic work function is in general not equal to the slope of the Richardson line and that in general the work function varies with temperature.

If we accept Becker's point of view, it is easy, by the use of his Eqs. (9) and (10), to calculate the thermionic work function from the above value of h and A. In column 1 of Table I is shown the rate of change of the work function with temperature. (See Eq. (10) of Becker's article.) Column 3 shows the values of the photoelectric work function determined by the method of Fowler. The values of the thermionic work function in column 4 are calculated from Becker's Eq. (9).

TABLE I. *Photoelectric and thermionic work functions of tantalum and variation with temperature.*

$\frac{dw}{dT}=\ln 120-\ln A$	T (°K)	*Work function (Volts)* Photoelectric	Thermionic
1.012×10^{-4}	293°K	4.13	4.13
	973°K	4.18	4.20

Since the temperature variation of the work function is a second order effect, the agreement between the temperature variation of the photoelectric and thermionic work function is better than one could expect. The absolute values, therefore, merely show that the data presented herein are consistent with Becker's conclusions.

The average value of the thermionic coefficient A is somewhat lower than the value 60.0 determined by Dushman and others.[10] Their value of 4.07 volts for the heat function is, however, in good agreement with the present value of 4.10 volts. The calculated value of A is particularly sensitive to an error in the temperature scale. In the present work, the correction for the emissivity of tantalum is greater than that applied by Dushman; hence, one would expect the value of A to be smaller than that determined by Dushman.

The writer has already pointed out that Fowler's theory of the photoelectric effect seems to hold to the same degree of accuracy for tantalum which was known to contain gas and for a sample which was thought to be gas-free. In this connection it is also interesting to note that the value for the photoelectric work function determined according to the method of Fowler agrees with the value of the thermionic work function of the *same surface* regardless of whether it is gas-free.

The writer is indebted to Professor C. E. Mendenhall for his cooperation and helpful interest during the progress of this work.

[9] Becker and Brattain, Phys. Rev. **45**, 694 (1934).

[10] Dushman and others, Phys. Rev. **25**, 338 (1925).