DETERMINING THE WORK FUNCTION OF TUNGSTEN THROUGH MEASUREMENT OF THERMIONIC EMISSION OF ELECTRONS AS A FUNCTION OF FILAMENT CURRENT

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ABSTRACT

In this paper the work function of tungsten is determined through the measurement of thermionic emission as a function of filament current. The current induced in an anode by the thermal emission of electrons from a hot wire filament was recorded. Measurements were made of the current across the anode as a function of the potential difference between the filament and the anode (repeating for different filament currents). The filament was placed in a chemical vacuum to remove the effects of the air particles on the observations. From this data the work function of the filament was calculated using the Richardson-Dushman equation modified for the effects of space charge. The use of this equation necessitated the input of temperature data for the filament which was taken to be proportional to the filament current. The experimentally derived value of the work function of tungsten was 4.511±0.0045 which is in good agreement with the standard values of between 4.52 and 4.32.

I. INTRODUCTION

When a current is passed through a wire, electrons and photons are emitted under the laws of thermionic and photoelectric emission. The purpose of this paper is to use the thermal emission properties of a tungsten filament to determine the work function of tungsten. As the current in the filament changes, so does its temperature and therefore the flow of emitted electrons. By placing the wire in a cylindrical anode the induced current across that anode can be measured as a function of the potential difference between the filament (the cathode) and the anode.

Electron emission from a hot wire induces a current, as a function of filament temperature, in the anode according to the Richardson-Dushman equation

$$J_{th} = AT^2 e^{\left(-ef/_{kT}\right)}, \qquad (1)$$

where J_{th} is the theoretical current induced in an anode, A is character of the surface, e is the charge of an electron, and f is the work function of the filament material. The relationship between the current put through the filament and the resulting temperature of that wire is given by

$$T = 735 + 1780\left(I_{fil}\right), \qquad (2)$$

where temperature is in K. Of course, not all electrons emitted by the filament will reach the anode. This creates a charge build-up in the space between the wire and the anode. This charge effectively reduces the force of attraction of the anode and in turn the work function f according to the relationship

$$f_{eff} = f - \sqrt{\frac{e^3}{pe_0}}\sqrt{E} \ , \qquad (3)$$

where E is the external electric field and $\mathring{a}_0$ is the permeability of free space. Therefore the current measured across the anode will also be affected. The measured current is given by

$$J_{meas} = J_{th} e^{\frac{e^3}{\sqrt{pe_0}}\frac{\sqrt{V}}{T}} \ , \qquad (4)$$

where V is the cathode-anode potential difference.

II. EXPERIMENT

To avoid having to consider the role of air in the motion of the electrons, the filament was kept in a near vacuum by utilizing a differential ion pump. The filament was placed within a cylindrical anode approximately 7/16 cm in length and 7/10 cm in diameter. In order to avoid complications arising from the curvature of the electric field at the edges of the anode, guard cylinders were placed at either end of anode (the guards were of the exact same design as the anode and were kept at the same potential *V*). See *Fig. 1(a)*.

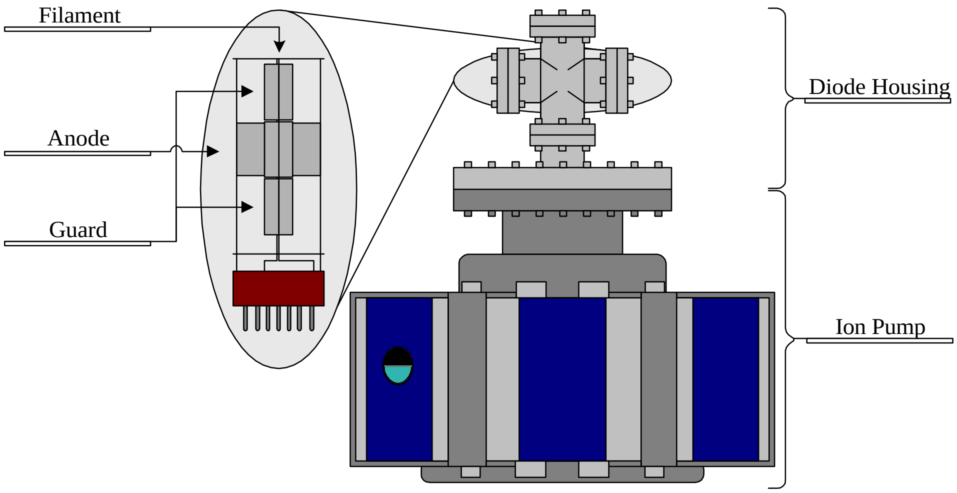

Fig 1(a): Schematic of filament diode setup and housing placement. Of the three faces on the diode housing, two were clear (the top and right ones were for viewing the filament) and one was the circuit interface (the left face).

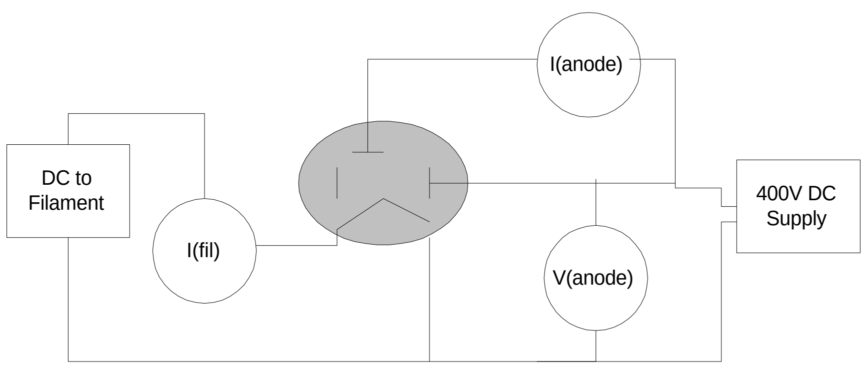

Fig 1(b): Circuit diagram of the experiment's electrical setup. The grey area in the center corresponds to the diode.

The power supply used to power the filament was a Hewlett-Packard Harrison model no. 6200B DC power supply (rated 0-40V, .75A/ 0-20V, 1.5A). The ammeter used to monitor the filament current was a W. M. Welch DC ammeter Cat. no. 30577 (rated to 10A). We used the 0-2.5A scale. The ammeter used to monitor the anode current was a Beckman Industrial digital multimeter, model no. DM27XL. Another digital multimeter was used to measure the voltage across the anode (this was a B+K Toolkit 2708).

The vacuum chamber was an Ultek D-I (differential ion) Pump 150LS, model no. 22-150. It was rated up to 150 L/S. The pump was powered by a Unit model 60-105 ion pump power supply.

A. Procedure

Once the experiment was set up (see *Fig. 1(b)*), a starting current for the filament was selected and carefully entered into the HP power supply. This supply has both coarse and fine current adjustment which allowed very fine tuning of the current. Once a current was dialed in, the voltage on the anode power supply was brought down to its lowest stable level. Data was taken at various levels of voltage by recording the voltage as indicated on the B+K multimeter and the current as shown on the Beckman multimeter. This data was immediately entering into a computer spreadsheet program where the plot of V vs. I was shown graphically. As the pattern emerged, we took extra measurements at specific voltages to fill in the 'gaps' in the graph as appropriate. This process was repeated for five filament currents. Each trial consisted of taking approximately thirty-three data points.

III. DATA

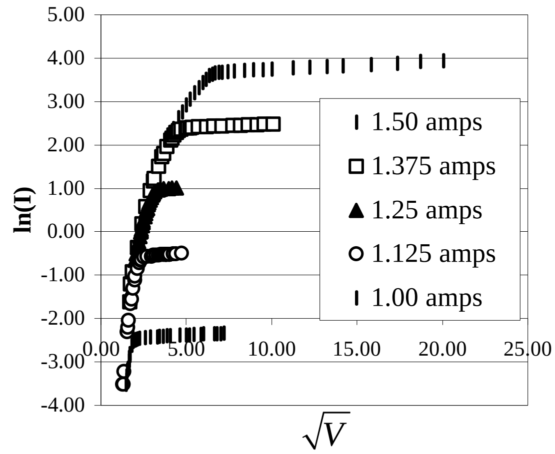

Fig 2(a). ln(I) vs. $\sqrt{V}$. The linear portion on the right of each data set intercepts the axis V=0 at the theoretical current.[1]

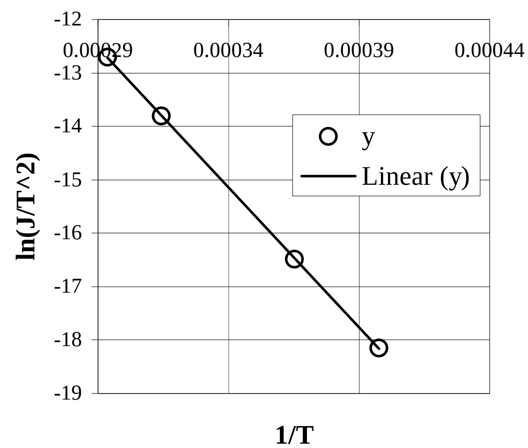

Fig 2(b). ln(J_{th}/T^2) vs. ($1/T$). The slope of this line corresponds to the work function f of the filament.[1]

As predicted, the measured current was the mixture of two behaviors. To verify the Richardson-Dushman equation, we plotted ln(I) vs. $\sqrt{V}$ (see *Fig 2(a)*). The start of the graph is a period of rapid growth. This then levels off to a linear portion that grows as a slight, but continuous rate. This linear portion, when extrapolated back to the axis $\sqrt{V}$ =0, will intercept at the natural log of the

[1] Error bars are shown, but are too small to be seen. Current I is given in amperes, voltage V in volts, and temperature T in Kelvins.

theoretical current as prescribed by equation (4). Once the current for each data set (for each temperature) is found, a plot of $\ln(J_{th}/T^2)$ vs. $(1/T)$ was made (see *Fig 2(b)*). The slope of this line is the work function of the material in question, tungsten.

A. Error analysis

While recording the data regarding voltage and current across the anode, it was noticed that the voltage measurement indicated on our meter fluctuated constantly, moving up or down a few hundredths of a volt several times a second. Our best effort went into trying to enter a voltage on the dial of the anode power supply such that these fluctuations were minimal or such that they were inconsequential to the recorded measurement (such as placing the error range about 3.13 V so that is would alternate between 3.14 and 3.12, we would then record this point as 3.1 V). Since the anode current measurements were taken at the same moment as the voltage measurements, they should have a good accuracy despite the fluctuations.

Using a least-squares fitting program[2], the data for each temperature (filament current) was entered and an approximation as to the intercept of the linear portion was made. By only entering the points that lie on the linear portion into the fitting program, and adjusting the errors such that the reduced $\div^2$ was close to 1, we were able to determine the theoretical J term and its uncertainty for each data set. The uncertainty for the 1.25 A was the highest of the five data sets taken, and eventually forced us to throw its point out of Fig 2(b). Since the remaining four points are in good agreement with each other and with theory, the decision was a good one. The measured slope was –52,373±52. This corresponds to

$$\left(\frac{-e}{k}\right)f\ , \tag{5}$$

where k is Boltzmann's constant (1.380×10^{-23} J/K) and e is the electron's charge (1.602×10^{-19} C). Solving for f gives a value of 4.5115±.0045 for the work function of tungsten.

IV. CONCLUSIONS

According to data given in a paper written by Dushman in 1930[3], the work function of tungsten is 4.52 (this being an average of three specific values given in the paper). In an earlier work[4], Dushman gives b_0 to be 52,650 (where b_0 is the measured slope of the $\ln(J_{th}/T^2)$ vs. $(1/T)$ plot according to

$$\log_{10}\left(J_{th}/T^2\right) = 1.779 - \left(b_0/2.303T\right), \tag{6}$$

where 1.779 is the approximate value of log A) by taking data form a variety of different tubes and averaging them with the least squares method. Citing another paper by Davisson and Germer[5] where better data was taken, Dushman notes that their data had an average value for b_0 of 51,860. Dushman makes a correction for the Schottky effect and arrives at the more proper result of 52,360. Each of these sources is in fine agreement with the data collected in this experiment. The CRC handbook[6] gives the work function of tungsten by thermionic emission to be 4.32.

Further corrections as to the exact behavior of the temperature of the filament could be made since at high temperatures, the relationship given in (2) does not hold. More accurate measurements of voltage and current across the anode would also lend to

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[2] LSQ Fit, a custom made Excel worksheet

[3] S. Dushman, Rev. Mod. Phys. **2**, 381 (1930).
[4] S. Dushman, Rowe, Ewald, and Kidner, Phys. Rev. **25**, 338 (1925).
[5] Davisson and Germer, Phys. Rev. **20**, 300 (1922)
[6] *CRC Handbook of Chemistry and Physics*, 83rd edition, D. Lide, ed. (2002-2003)

better results. A better approximate for the surface character of the filament or perhaps the inclusion of the exact dimensions of the filament and the anode, again, would lead to more accuracy.

V. ACKNOWLEDGMENTS

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