Investigation of the Thermionic Emission Phenomenon Using a Tungsten Vacuum Tube Diode

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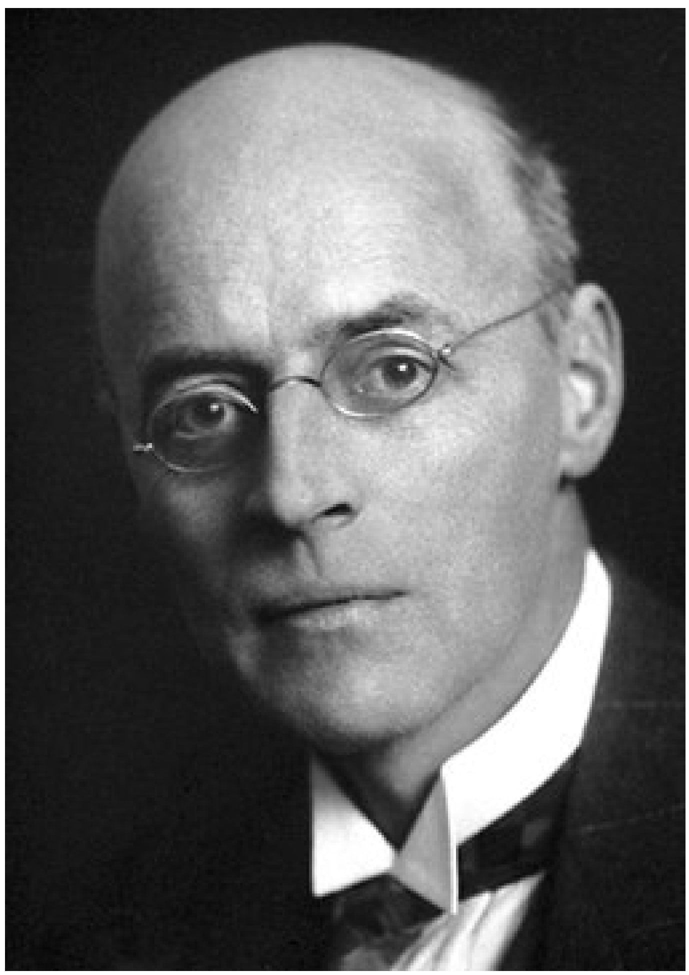
The phenomenon of thermionic emission is an incredibly interesting and useful effect, and is the basis for a variety of important modern technologies. This experiment sought to investigate the conditions of this effect to confirm Richardson's law; alongside obtaining a value for the work function of tungsten. Data from the experiment strongly supported the validity Richardson's law, however the value for the work function of tungsten derived was slightly lower than expected. The possible reasons for this discrepancy are discussed.



Owen Willans Richardson, who investigated thermionic emission and discovered Richardson's law. [1]

I. INTRODUCTION

The thermionic emission phenomenon was first reported 1853 by Edmond Becquerel, however this was before the modern model of the atom and the concept of an electron as a particle[2]. The phenomenon was rediscovered multiple times by various scientists, particularly Thomas Edison who created the first 'Edison effect' bulbs; a technology which was then further developed into the modern vacuum tube diode used in this experiment.

After the work of J.J Thomson in 1897, the scientific understanding of electricity greatly matured following the discovery of the electron. This led physicist Owen Willans Richardson to begin work thermionic emission, later receiving a Nobel Prize for it. It is in this work Richardson's law was discovered. The law is as follows for any metal [3]:

$$n = AT^2 e^{\frac{-\phi}{k_B T}} \tag{1}$$

Where n is the number of electrons emitted from the surface of the metal per unit area, T is the temperature in Kelvin, k_B is Boltzmann's constant, ϕ is the work function of the metal and A is a universal constant comprised as follows:

$$A = \frac{4\pi k_B^2 m}{h^3} \tag{2}$$

Where m is the mass of an electron and h is Planck's constant.

This electron emission is possible due to the fact that although the average thermal energy of an electron is far below what is required to overcome the forces holding it within the metal lattice, there will be a few electrons with enough energy to escape the surface given they have an appropriate velocity. The distribution of electron energies in this case is well approximated by a Maxwell-Boltzmann distribution. *(see FIG. 1)*

The red, green and blue curves in *FIG. 1* represent the energy distributions of electrons at various metal temperatures (red being the highest temperature). It is both evident and intuitive that a higher temperature metal will have a larger proportion of electrons with enough energy to escape and this is where the temperature relationship in *EQ. (1)* arises.

In practice at low anode voltages (approx. less than 10 Volts), not all of the electrons emitted by the cathode in a vacuum tube diode reach the anode, as many are repelled back into the metal lattice due to

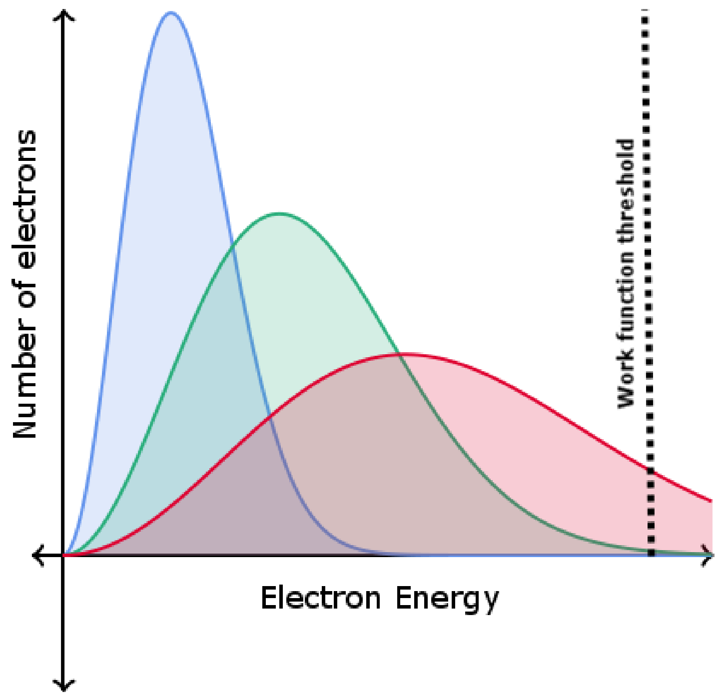


FIG. 1. The distribution of free electron energies in a metal lattice

the 'space charge' accumulated between the cathode and anode. Only the electrons drained in the anode are replaced. The system is said to be 'space charge limited'. At higher anode voltages, all of the emitted electrons are able to reach the anode and the system is considered 'saturated'. In this case the anode current depends largely on the dimensions, temperature and materials used in the diode. A small increase current with increasing anode voltage is possible, this is due to a reduced potential barrier for electrons escaping the cathode, a phenomenon known as field emission[6]. This point of saturation current is the critical piece of data in this experiment necessary determine the validity of Richardson's law as at this point the current will be equivalent to n in *EQ. (1)*.

II. EXPERIMENTAL DETAILS

This experiment was separated into two stages; the calibration phase and the high voltage measurement phase. The calibration phase is necessary as the temperature of the tungsten cathode needs to be be found out to . This temperature is directly related to the resistance of the cathode as follows:

$$R = R_{20}(1 + \alpha\theta + \beta\theta^2) \tag{3}$$

Where R_{20} is the resistance at 20 $°C$, θ is the temperature in degrees and α and β are constants of proportionality with values of $5.241 \times 10^{-3} degree^{-1}$ and $7 \times 10^{-7} degree^{-2}$ respectively[5]. In order for this relationship to be used the value of R_{20} needs to be found, this is done using by passing a low current through the cathode (so not to heat it). Using the central Wheatstone bridge section of the circuit (see FIG. 2), the resistances of R1 and R2 were balanced so that current across the Wheatstone bridge was zero, the circuit is such that the value of R_{20} is the ratio between R_2 and R_1[7]. Several measurements with various resistance combinations and currents between $1 - 100mA$ (these low currents should not heat the cathode significantly above room temperature) were taken and the value of R_{20} was determined as $0.61 \pm 0.04\Omega$.

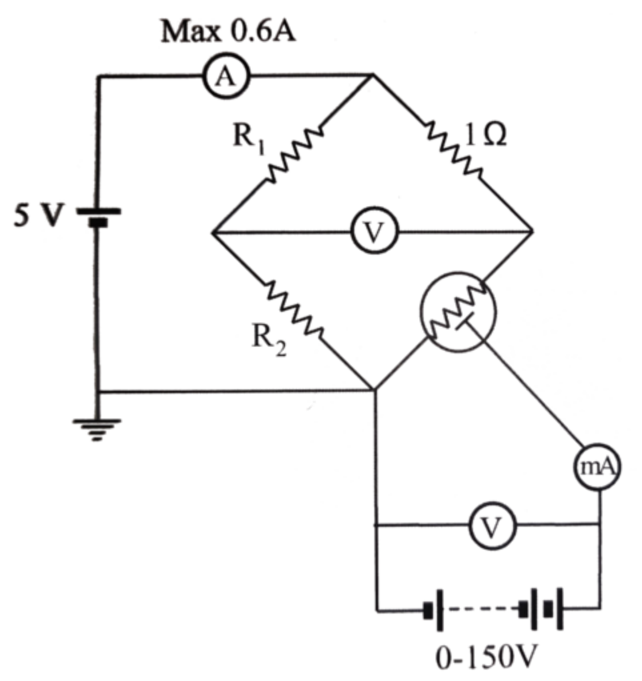


FIG. 2. A diagram of the circuit setup in this experiment

Once the value of R_{20} was found, the temperature for various cathode voltages (using Ohm's law) could be obtained using *EQ.1*. Anode current data was then collected and plotted vs anode voltage for various cathode temperatures. (See *FIG.3*)

III. RESULTS AND DISCUSSION

It is evident that higher voltage data, corresponding to higher cathode temperature has lower uncertainties and this is due to the limits of the equipment i.e. least count error is higher for lower temperatures. The data seems to fit the shape of the theoretical curve incredibly well across the whole range of cathode

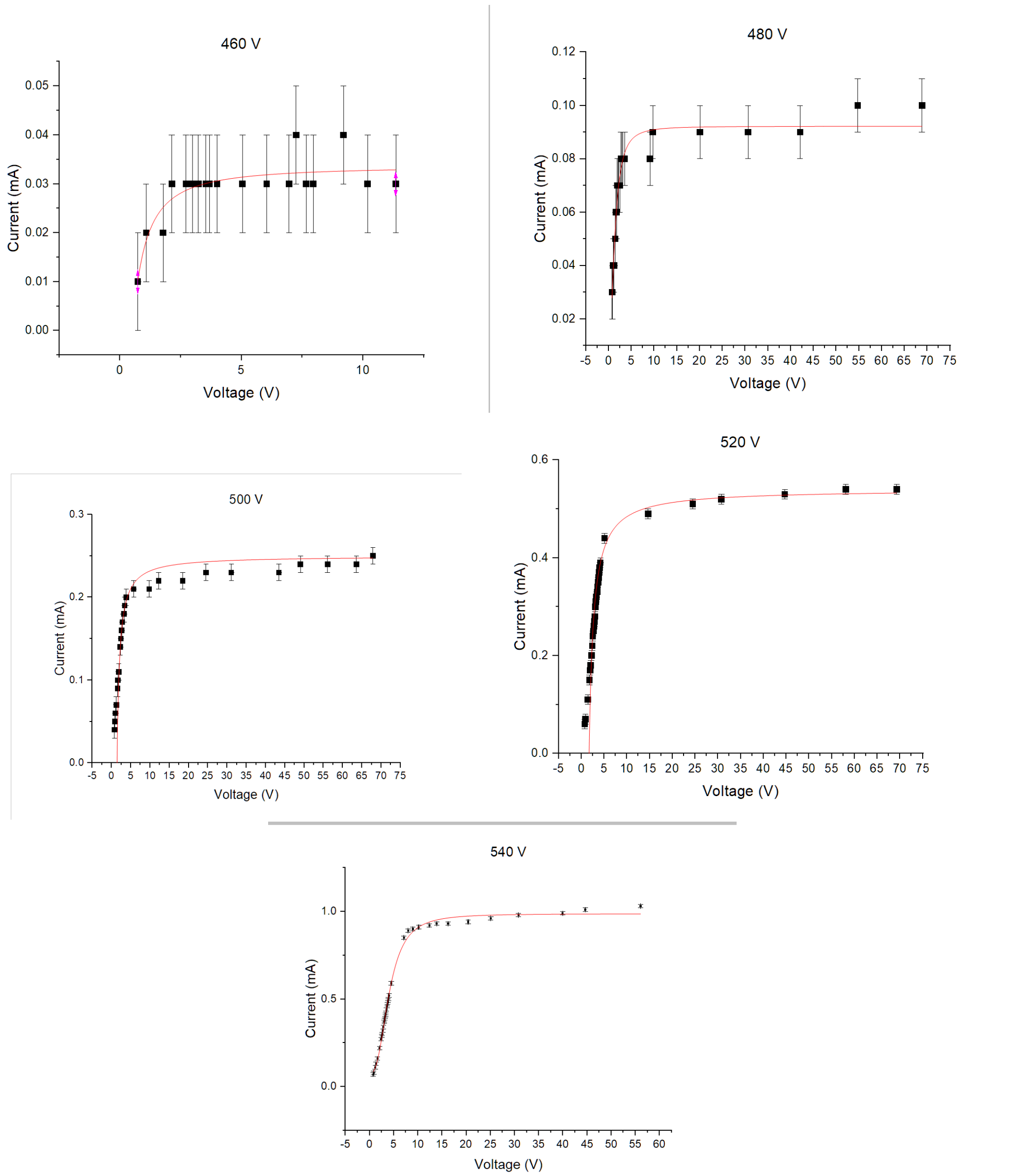


FIG. 3. Graphs of anode current vs anode voltage for various cathode voltages. The red lines on the graphs are not exact statistical fits but are used to demonstrate the shape of the curve theoretically expected [3]

temperatures. There is a clear point in each where the saturation current is reached and these currents were recorded. If the natural logarithm of each side of *EQ. (1)* is taken, the following is can be deduced:

$$ln(\frac{I_s}{T^2}) = \frac{-\phi}{k_B} \times \frac{1}{T} + ln(eA) \tag{4}$$

Where e is the charge of an electron $1.602x10^{-19}C$. Therefore, plotting $ln(\frac{I_s}{T^2})$ vs $\frac{1}{T}$ will provide validation to Richardson's Law provided the graph has a constant gradient which when multiplied by $-k_b$ should be simply result in ϕ, the work function of tungsten.

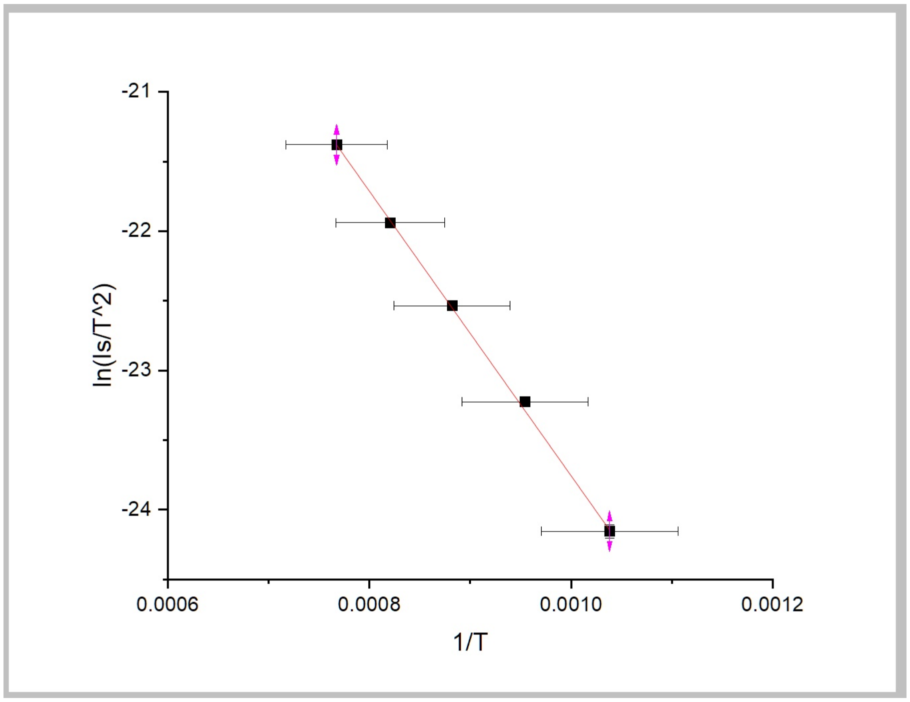


FIG. 4. Graph of $ln(\frac{I_s}{T^2})$ vs $\frac{1}{T}$, the red line is a a linear fit of the data.

From the gradient of graph we get a result of:

$$\phi = 0.88 \pm 0.02eV \tag{5}$$

The uncertainty in this result was calculated using the partial differentiation method. The full equation used to obtain this uncertainty can be found in the appendix. This work function is of the same order expected although a little smaller than the expected value ($4.5eV$)[5]. There my be several reasons for this discrepancy; one is that often in vacuum tube diodes, the filament metal is plated in a different metal and doing this deliberately lowers the work function to increase the anode current. This would typically reduce ϕ by $2eV$ so this cannot explain explain the full discrepancy in our result however. The data in the final plot conforms to a straight line fit very well, therefore systematic error in one or more of the measurements is likely to be the explanation for the final discrepancy. Imperfect calibration and use of R_{20} to calculate the cathode temperature is the most probable cause.

IV. CONCLUSIONS

The conclude Richardson's Law has been strongly demonstrated by our data and the work function for the filament in the vacuum tube diode has been calculated as the following:

$$\phi = 0.88 \pm 0.02eV \tag{6}$$

Additionally it has been found that the calibration phase of the experiment needs to be conducted carefully to avoid drift of calibration errors in order to produce accurate results.

V. APPENDIX

Errors on the initial measurements were calculated by combining the least count error with the standard deviation on the mean.

For the final value the error was calculated using the least squares equation below:

$$\Delta\phi = \sqrt{(ln(\frac{I_s}{T^2} - 2)^2 \Delta T^2 + (\frac{T}{I_s})^2 \Delta I_s^2} \tag{7}$$

VI. REFERENCES

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