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Lab 1: Vacuum Diode Current-Voltage Characteristics

1 Purpose

The aim of the experiment is to 1) measure the current flow through the plate of a filament circuit as a function of voltage 2) extrapolate the temperature of the filament at a lower voltage 3) show how a diode can be used as a rectifier.

2 Theory/Procedure

We set up a simple vacuum diode to analyze current flow. The cathode is a filament circuit that can be set to different heating voltages. The anode is a plate circuit which is connected to an ammeter. Thermionic emission describes the process where electrons are released from metal surfaces. At high enough temperatures, electrons in the filament metal can escape from the metal. The "work function Φ" provides the necessary energy needed for the electrons to escape. If the plate is at a positive potential, the electrons will be attracted to the plate and thus will be pulled across the gap, generating current. This is true since electrons are negatively charged and so will point in the opposite direction as the electric field. These electrons will experience a force $\mathbf{F} = q\mathbf{E}$. The current that can flow between the filament and the plate is limited. The cloud of electrons between the filament and plate repel electrons escaping from the metal back. As this cloud of electrons increases, there exists a maximum current density that can be achieved.
To conduct the experiment, we connect a variable AC supply to the circuit (as shown below in Figure 1a) to heat the filament. Then we turn on a DC power supply to create voltage on the plate. To measure the AC voltage on the filament, we connect a multi-meter to the circuit. In the first set of data points, we set the AC to be 5 V, and then measure and record the plate current as as we steadily increase the DC plate voltage. We do the same thing for a filament voltage of 2.5.
In the second part of the experiment, we show how a diode can be used as a rectifier by rearranging the circuit as shown in Figure 1b. We then use the function generator to setup a 100 Hz, sine wave. Then we use the oscilloscope software to view the two channels on the screen and record the data.

(a) Part One (b) Part Two

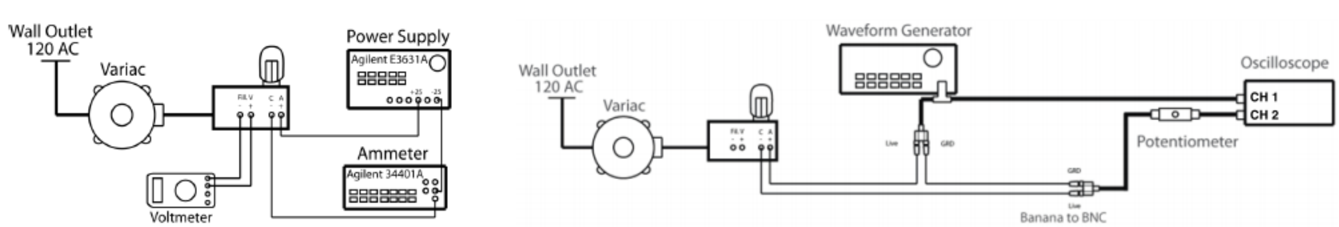


Figure 1: Experimental Circuit Setups [1]

3 Discussion

Question 1: The thermionic emission current density in the 5 V filament is given by:

$$J_{th} = A_o T^2 e^{-\frac{\phi}{kT}} = 100(980)^2 e^{-\frac{1}{(8.617*10^{-5})(980)}} \quad (1)$$

$$\boxed{J_{th} = 691.23\frac{A}{m^2}} \quad (2)$$

where A_o is the Richardson constant (100 $Am^{-2}K^{-2}$ for this material), Φ is the work function (1 eV for this material), T is the temperature in K, and k is the Boltzmann constant ($8.617 * 10^{-5} eVK^{-1}$) To extrapolate the temperature of the 2.5 V filament, we know that the cathode area is $S = 2.3 * 10^-4\ m^2$, and the final I value (data in table below) was 57.452 mA. Thus,

$$J_{th} = \frac{I_{final}}{S} = \frac{57.452 * 10^3}{2.3 * 10^{-4}} = 249.79 \quad (3)$$

$$249.79 = A_o T^2 e^{-\frac{\phi}{kT}} = 100T^2 e^{-\frac{1}{(8.617*10^{-5})T}} \quad (4)$$

$$\boxed{T = 912.55} \quad (5)$$

Question 2: We received the following data in the lab:

Plate Voltage, V(V)	Plate Current, I(mA)
0	1
2	7.25
3	11.16
4	15.39
5	19.99
6	25.01
7	30.59
8	36.80
9	43.41
10	49.88
12	62.06
14	75.22
16	89.51
18	105.72
20	129.21
25	180.77
30	235.16
35	292.12

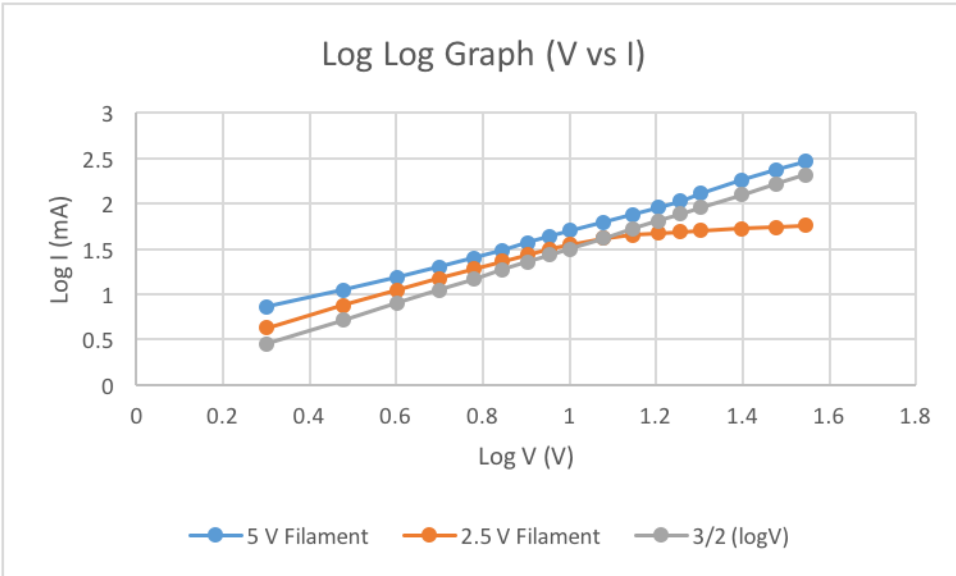
Table 1: V = 5V, T = 980 K

Plate Voltage, V(V)	Plate Current, I(mA)
0	.018
2	4.241
3	7.517
4	11.105
5	14.888
6	18.824
7	22.875
8	27.100
9	31.303
10	35.178
12	41.014
14	44.857
16	47.133
18	48.578
20	49.989
25	52.517
30	54.925
35	57.452

Table 2: V = 2.5V, T = 912.55 K

This data does satisfy the Child-Langmuir Law. The graph below is a log log plot that shows the relation between log V and log I for both filament voltages is linear with a slope roughly equal to 3/2. The thermionic current emission density does affect the current we measured.

Figure 2: Child Langmuir Visual (Log Log Graph)



It sets an upper bound on the value of I/A, so the I values start leveling off when they reach the thermionic current emission density.
The Child-Langmuir Law is always applicable for the 5 V filament (for voltages > 0). However, it stops being applicable in the 2.5 V case after the data has sufficiently converged ($V > 14$). This is clear on the graph by the flat-lining orange bar. This deviation occurs because the current density starts to reach the upper bound on the thermionic emission current density.

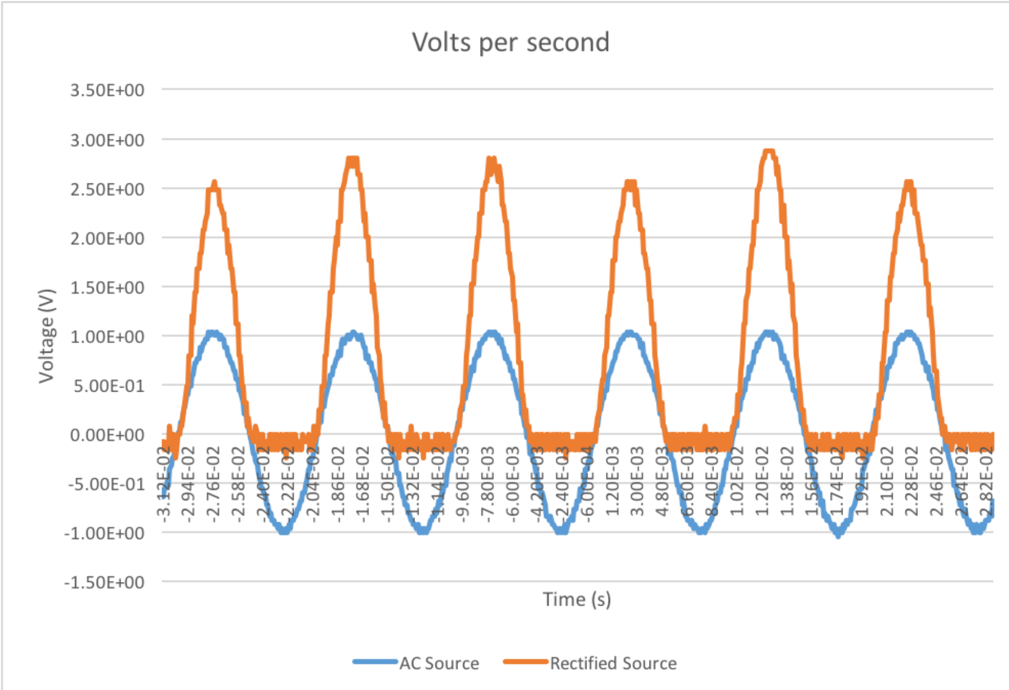
Question 3: When there is no applied voltage between the plate and the cathode, the current is not truly zero because the temperature is still high enough that it provides enough energy for electrons to leave the filament metal with nonzero velocity. The electrons are still drifting across the material even though they aren't between actively pulled by a potential difference.

4 Conclusion and Applications

This lab demonstrates the process of creating a diode in a circuit to allow the process of rectification. The vacuum diode in our experiment is created as a result of the thermionic emissions of electrons off the filaments and a potential difference over a plate circuit.

In the last part of the experiment we used the function generator to visualize how the diode can be used as a rectifier. Notably, the diode only allowed current to flow in one direction. This is shown in the following data:

Figure 3: Rectified Signal Graph



The input sine waves are just AC current. The rectified half waves provide a nonzero DC component.

This rectification of signals is very important. By only allowing current to flow in one direction, rectifiers can convert an AC source to a signal with a DC component. This is crucial because the power distribution system from wall socket to wall socket uses an AC system, but most devices use DC voltage to operate. These devices range from cell phones to TVs to electric vehicles. As a result, demonstrating the conversion of AC to DC power is very important.

5 References

[1] Laboratory 1 Manual, *Vacuum Diode Current-Voltage Characteristics*, Brown Engineering 0510