

# Modern Physics Lab

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## Thermionic Emission

### Purpose of the experiment

- qualitative understanding of electron emission from solids and electro-statics

#### Introduction

Metals can be approximated as consisting of an array of immobile positive charges (ions) immersed in a free electron gas. This model was originally developed by Drude in 1900. It treats the electrons using the kinetic theory of gasses. It is a useful model for providing intuition and estimates of physical properties of metals. It is not, however, able to describe many important properties which require the modern quantum theory of solids.

In the Drude model, the electrons move like a gas through the metal. The resistivity ( $\rho$ ) of the metal (or equivalently the conductivity ( $\sigma$ )) results from the electrons being knocked off course by scattering processes inside the solid. These collisions act to achieve thermal equilibrium between the electrons and the metal. The free electrons are not tightly bound into the solid so that if they are given enough energy they can escape from the surface. The thermal energy provided by heating the metal can be converted to kinetic energy of the electrons in the scattering process. This increased kinetic energy allows them to overcome the attractive forces of the solid and to escape into the surrounding space. Heating a metal filament is thus a good way of producing electrons. This technique is used in many types of research equipment some of which are included in this course. The same technique is used in television sets.

A somewhat more rigorous discussion of thermionic emission considers a simple quantum theory of solids. We can model an electron in a metal using the "particle in a box" model. Normally this

model assumes that the box has infinite potential barriers and nothing can escape. We will modify the model by assuming that the walls are now finite. We will picture an energy well with walls of height  $V_0$ . The energy levels derived for the particle in a box model are still approximately correct if the barrier is high enough. At  $T = 0$  K, all the allowed energy levels in the well up to  $E_F$  (the Fermi energy) are filled. All levels above the Fermi energy are empty. The Fermi energy of the metal is located at an energy  $W_0$  (the work function) below the top of the well. At higher temperatures the picture is not quite as simple. The sharp cut off in filled energy states at the Fermi energy is replaced by a transition region of width  $2kT$  (where  $k =$  Boltzmann constant) centered at the Fermi energy. Fermi energies and work functions of most metals are typically a few eV. (For tungsten the work function is about 4.5 eV). Thermal energies ( $kT$ ) at room temperature are about 0.026 eV. [This is a handy number to remember. It is easier to remember as 1/40 of an eV.] So at room temperature the energy state distribution still looks very similar to the  $T=0$  case. However, remember that room temperature is NOT zero temperature. At high enough temperatures, some electrons will have high enough energies to escape from the well (energies greater than  $V_0$ ) causing thermionic emission.

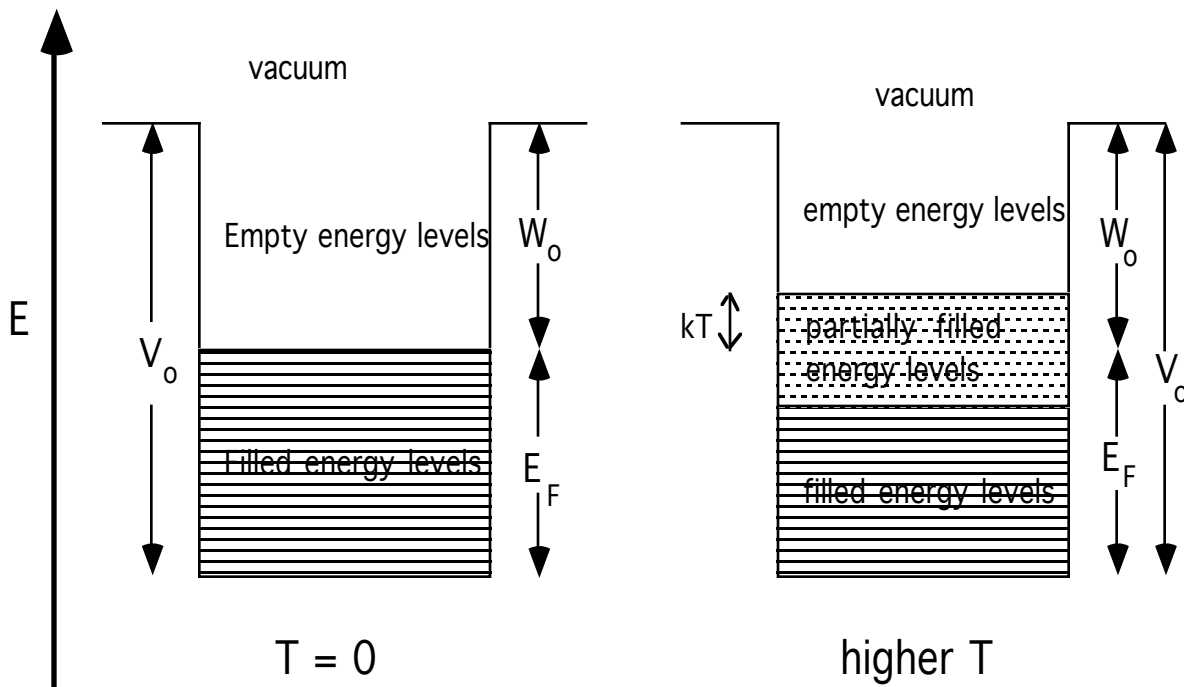


Figure 1. Energy level diagram of metals at  $T = 0$  and at higher  $T$ .

The current ( $I$ ) emitted from a metal is found to be a function of both its temperature ( $T$ ) and work function ( $W$ ). The Richardson-Dushman equation gives this relationship as

$$I = A (kT)^2 e^{-W/kT}$$

where A is a constant which depends on the material and geometry and k is Boltzmann's constant.

The planar diode used in this experiment (Teltron Ltd. #TEL 520) consists of a filament and two circular plates inside an evacuated, clear glass bulb. The inside surface of the the bulb has been made electrically conducting to eliminate external electrostatic field effects. (Remember from your Electricity and Magnetism class that the electrostatic field inside a conductor is always zero.) The plates and filament are parallel providing a planar geometry. The filament is pure tungsten wire mounted on two leads connected to 4 mm diameter sockets on the neck of the bulb. The filament is heated by alternating current for the thermionic emission measurements so that the average DC potential along the filament is effectively zero. Connection to the plate is made by a 4 mm plug mounted on the top. The performance of the diode is improved by using a second circular plate which is attached to one of the filament leads. This provides a more uniform electric field between the electrodes. The diode can be mounted in the Teltron Universal Stand (#TEL 501).

Diode Specifications:

MAXIMUM filament voltage: 7.5 V                      Optimum plate voltage: 500 V

MAXIMUM filament current: 3 A                      Typical plate current: 3 mA

**BE CAREFUL NOT TO BURN OUT THE FILAMENT !!**

**Experiment:**

When the filament is heated electrons can escape from the material into space. By applying a potential between the filament and the upper circular disk, the electrons can be collected. This experiment can generate a lot of data. Your mission is to interpret that data and present it in a manner which helps the reader to understand what is going on. This will involve making graphs and carefully choosing which variables to plot and what scales to use.

The filament is heated by passing a current through it. Changing the AC voltage used will allow you to pass various amounts of current. You may want to monitor the current through the filament with a meter. You may use the set levels of the power supply or use a Variac (variable AC transformer) with a step down transformer to get into the right range of voltages.

Connect a DC power supply between the filament and the collector plate as shown in Figure 2. The power supply should be 500 V maximum and have a maximum current of 5 mA. A current meter capable of measuring 0 - 3 mA should be used to measure the flow of electrons to the collector plate. (If a more sensitive meter is available to measure 5-50  $\mu$ A currents, this will allow measurements at lower potentials).

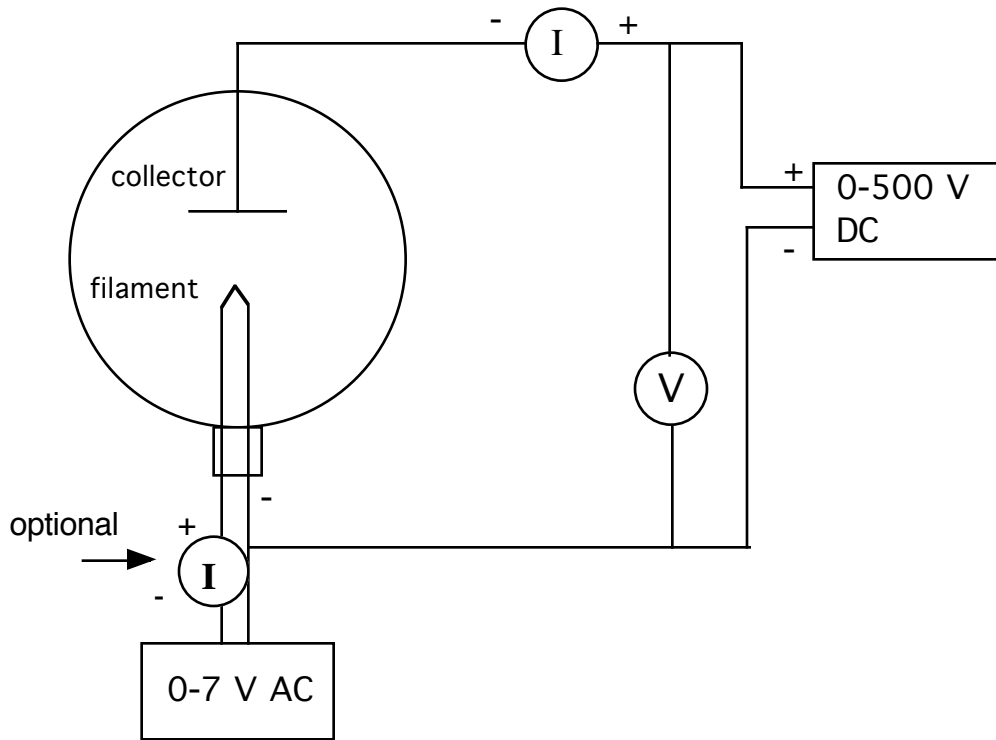


Figure 2. Experimental set-up.

With the filament at room temperature, apply a small potential to the collector plate. Do you measure any current? Should you? Increase the potential. Do you see any changes?

With no potential on the collector, try heating the filament. You should observe a small current (about 5-50  $\mu\text{A}$ ). Now try increasing the potential on the collector and observe the current. Try several different filament temperatures (different voltages on the power supply).

You have now established that both filament temperature and the potential between the collector grid and the filament effect the current of electrons between the filament and collector. Explore the characteristics of this vacuum diode. How do the temperature and voltage influence the current?

Why do the temperature and voltage influence the current? You should plot electron current vs. applied voltage for several filament temperatures. Discuss the shape of your curves. Are they linear, exponential, saturating? Why? [If you see a linear relationship between collector current

and collector potential over a wide voltage range (400 V), you may have the experiment hooked up wrong.] Looking at all of your data, do you see anything else to plot that might be interesting?

This experiment involves something very common in physics. Your detected signal depends both on the properties of the source (filament) and on the detector (collector plate). You may need to take this into account in explaining your data.

### References

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