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RSPG – Experimenting with Low Temperature Plasma

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Abstract

This paper describes a low temperature plasma physics and visible spectroscopy experiment set-up and run by A level physics students. Results are presented from the measurement of the breakdown voltage for an argon plasma, successfully measured for a wide range of pressures. The minimum breakdown voltage from these results has been used to find an experimental value of ionisation energy for argon. In addition, the results from a visible spectroscopy system are also presented, using a fibre optic array coupled to a monochromator and microchannel. The first set of results from this study is shown as a plot of relative intensity as a function of wavelength.

Introduction

Plasma is the most abundant form of matter[1] and was first identified by Sir William Crookes in 1879[2]. The word 'plasma' was first applied to ionised gas by Dr. Irving Langmuir, an American physicist, in 1927[3]. Plasmas consist of a collection of free moving electrons and ions. Energy is required to remove electrons from atoms to create ions; this energy can come in various forms including thermal, electrical or light. If there is insufficient energy to sustain the plasma, the particles recombine into atoms to form a neutral gas. Plasmas can be accelerated, directed and confined using magnetic fields. This allows them to be controlled and applied to a wide range of practical uses including space propulsion, industrial plasma processing, nuclear fusion, positron storage in dusty plasmas, plasma arcs, torches, steel recycling and lighting. Plasmas usually exist at high temperatures as high energy is required to sustain them, but they can also exist at lower temperatures.

Low Temperature Plasma System

The direct current (DC) low temperature plasma system used for the study is an Edwards S150 sputter coater, comprising two conducting plates (electrodes) separated by 10 cm. A potential difference of up to 1.5 kV is applied across the plates in a relatively low pressure environment of argon gas of 0.15 Torr (Torr is a unit of pressure where 1 Torr ? 133.3 Pascals). The electrical potential difference between the plates is enough to break down and ionise the gas to form a plasma. A picture of the argon plasma used in this experiment is shown in figure 1. The characteristics of the plasma are controlled by four variables: potential difference, distance between the plates, the type of gas used and the gas pressure.

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Photograph of the argon plasma used in the project.

Figure 1: Photograph of the argon plasma used in the project.

Paschen Law Experiment

In 1889, Friedrich Paschen developed a law to describe the minimum breakdown voltage of a gas as a function of the electrode spacing, d, and the pressure of the gas, P. The breakdown voltage is the potential difference necessary for a gas to discharge and become plasma. The process in which this happens is called a Townsend discharge, named after John Sealy Townsend. The Townsend discharge is a gas ionization process whereby free electrons are accelerated by a strong electric field and cause an electric current to flow through a gas. This current is then continued by avalanche multiplication caused by the ionization of molecules by ion impact. In this avalanche, positive ions drift towards the cathode (the negative electrode), while free electrons drift towards the anode. If the electric field is strong enough, the free electrons gain enough energy to liberate further electrons when they next collide with other molecules. These free electrons then travel towards the anode and gain enough energy from the electric field to cause impact ionisation when the next collisions occurs, creating more electrons; and so on. This process is a chain reaction of electron production which depends on the free electrons gaining sufficient energy between collisions to keep the avalanche going.

By considering Townsend's first coefficient, ? (units of m^{-1}), the breakdown voltage can be shown as a function of potential difference, V, using the following equation:

$$\alpha = \frac{kTd\exp(1 - \ln V)}{\sigma}$$

where *T* is the temperature of the gas (K), *?* is the cross section of the ion-electron collision (m^2), *k* is the Boltzmann constant (1.38 x 10-23 J K^{-1}) and *d* is the probability of ionising a gas per unit length of path (m^{-1}).

To keep the discharge going, free electrons must be created at the cathode's surface. Otherwise, there will be no electrons for ionisation to occur. This is possible because the ions hitting the cathode release secondary electrons upon impact. The mean number of generated secondary electrons per ion, *?*, is given by:

$$\gamma = \frac{1}{\exp(\alpha d - 1)}$$

? is also known as Townsend's second coefficient (it has no units).

Method

The aim of the experiment was to discover the relationship between the breakdown voltage of argon as a function of pressure and distance between the cathode and anode. This was achieved by varying the pressure in the gas discharge chamber in the Edwards S150 Sputter Coater. Unfortunately, the distance between the electrodes in the chamber is fixed at 12.5cm ±2 mm, so the only pressure could be changed for the experiment. A voltmeter was connected in parallel to the electrodes, in order to record the potential difference across the discharge. An analogue Pirani gauge was used to measure the argon gas pressure to within ±0.02 T. The pressure in the gas chamber was varied by altering the opening of the gas input valve. The breakdown voltage of the gas was measured by gradually increasing the voltage applied to the electrodes, to the plasma has been just visible in a dark room. The potential at which this occurred was recorded as the breakdown voltage to within an absolute error of ± 3V.

Results

The results from the experiments are shown by figures 2(a), (b) and (c) in which minimum breakdown potential difference has been plotted against argon gas pressure. For the first experiment, figure 2(a), thirteen results were recorded and the graph shows a Paschen curve trend, with many results recorded around 0.2 T to accurately locate the minimum point of the curve. This is considered to be at a voltage of 138 V and a pressure of 0.17 ±0.02 T. For the second experiment, thirty results were recorded to provide a wider range of values. Once again, a large number of these were measured at around 0.2 T, and the minimum of the graph was located at 133 V and 0.19 ±0.02 T. For the third and final experiment, twenty results were recorded and this experiment locates the minimum of the curve at 137 V and 0.18 ± 0.02 T.

Plots (a, b and c) of minimum breakdown voltage against argon gas pressure.

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Figure 2a: Plot of minimum breakdown voltage against argon gas pressure.

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Figure 2b: Plot of minimum breakdown voltage against argon gas pressure.

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Figure 2c: Plot of minimum breakdown voltage against argon gas pressure.

The average pressure for the minimum breakdown voltage from all three results is 0.18 T (24 Pa). From this data, ? is calculated to be 0.013 ± 0.001 m^{-1}, using *T* = 295.15K (room temperature) and ? = 3.5×$10^{-20}$$m^2$(calculated by McDaniel)**4** . ? is therefore calculated to be 6000 ± 600 using ? and *d* (expressed to 2 s.f.). The ionisation energy for argon was therefore calculated to be (8.3 ± 0.8) x 10^{-17} J, by taking the average of the minimum breakdown voltages discovered from the experiments, which is 136 ± 14 V. This is a factor of 33 times larger than the published ionisation energy of an argon atom of 2.5 × 10^{-18} J; experimental or human error could be factors, so carrying out more trials would be advantageous.

Visible Spectroscopy System

Atomic emission spectroscopy helps to identify the intensity of light at different wavelengths produced by a plasma to determine the elements it contains. This type of spectroscopy is most commonly performed with a spectrometer and detector. For this experiment, a combination of a monochromator, photodetector and oscilloscope has been used to scan the visible wavelengths of an argon plasma.

Optical fibres have been used to transmit the light emitted from the plasma to the entrance slit of the monochromator. Optical fibre cables work by the principle of total internal reflection. When light enters a less optically dense medium (lower refractive index) from an optically denser medium (high refractive index), the emergent ray is reflected from the point at which the two mediums meet when the incident angle is higher than the critical angle. The core of the optical fibre cable is often made out glass or plastic and has a reflective index higher than the cladding surrounding it. This means that the light travelling down the cable bounces off the side at the same angle each time, so it can travel further. For optical fibre cables used over a relatively short range, the diameter of the core can be increased with negligible adverse effect on the quality of the light being transmitted due to the short distance of the transmission. In the experiment, initially 1mm optical fibres were used, but the light received and transmitted by the cables was not sufficiently intense. The 3mm diameter fibre optics were added to the 1mm fibre configuration, which vastly improved the light level received and transmitted by the cables to the monochromator and increased the signal output to the oscilloscope.

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Figure 3: Entrance and exit slits, mirror and diffraction grating set up for a monochromator, illustrating the light ray paths (image source).

A monochromator is an optical device that transmits a mechanically selectable narrow band of wavelengths of light, chosen from a wide range of input wavelengths. The wavelength of the atomic spectral line gives the identity of the element, while the intensity of the emitted light is proportional to the number of atoms of the element. A diagram of a common Czerny Turner design monochromator set-up is shown in figure 3. Light (A) is focused onto an entrance slit (B) and is collimated with a curved mirror (C). The collimated beam (light rays are parallel) is diffracted from a rotatable grating (D) and the dispersed beam is re-focused by a second mirror (E) at the exit slit (F). Each wavelength of light is focused to a different position at the slit, and the wavelength which is transmitted through the slit (G) depends on the rotation angle of the diffraction grating. The monochromator used in this experiment has a microchannel plate coupled to the exit slit, which acts as a photodetector.

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Figure 4: Diagram to show the structure and electron gain process for a microchannel plate (image source).

A microchannel plate is made out of many vacuum tubes called microchannels, which are spread across the microchannel plate in parallel with each other, as shown in figure 4. A potential difference of 1 kV is applied across the microchannel plate. When the photons from the plasma arrives at the photodetector, the incident photons strike the photocathode material of the photomultiplier. Due to the photoelectric effect, electrons are liberated from the photocathode material. As the incident photon is absorbed by the electron which exists in an orbital around the atom of the photocathode material, the electron gains enough energy to be freed from the atom. The number of primary electrons produced is dependent on the number of photons of light entering the photodetector, and is therefore determined by the intensity of the light exiting the monochromator. The primary electrons produced are directed by a focusing electrode toward an electron multiplier, the microchannel plate, as shown by the schematic diagram of electron gain in figure 5.

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Figure 5: Schematic diagram of the microchannel plate electron gain process (image source).

When the primary electrons arrive at the microchannel (also known as a dynode), they are accelerated by the electric field applied across the micro channel, directed towards the wall of the microchannel and collide with it. Due to the phenomenon of secondary electron emission [6] , more electrons of reduced energy are produced. These secondary electrons are also accelerated by the electric field further along the microchannel and more collisions occur with the wall, so the same process repeats with evermore increase in the number of electrons produced. The electrons produced are picked up by an anode which produces a current proportional to the number of photons initially entering the photomultiplier. This process of multiplying electrons makes it possible to detect very small electromagnetic signals, in the form of photons entering the photodetector initially.

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Figure 6: A graph of relative intensity as a function of wavelength for the argon plasma used in this study.

The output signals from the photodetector for the different wavelength settings of the monochromator, are input into an oscilloscope allowing the relative intensities to be recorded. The initial set of results of relative intensity has been plotted as a function of wavelength and is shown in figure 6. The next step for this study will be to compare the characteristic peaks of the graph with published wavelengths to identify the chemical composition of the argon plasma and any impurities and contamination that may be present.

Summary

Results have been presented from an experimental study of plasma physics and visible spectroscopy for a low temperature argon plasma. The breakdown voltage for the argon plasma has been successfully measured for a wide range of pressures and repeated three times. The minimum breakdown voltage has been used to find an experimental value of the ionisation energy of argon, $(8.3\pm0.8) \times 10^{-17}$ J per atom. This value compares well with the published value of 2.5×10^{-18} J per atom, though further experiments could help to eliminate any sources of error.

A visible spectroscopy system has been set-up for the argon plasma using a fibre optic set-up coupled to the entrance slit of a monochromator. The monochromator itself is connected to a microchannel plate which has been used to measure the relative intensities of the argon plasma. The first set of results from this study is shown as a plot of relative intensity as a function of wavelength. The next step will be the identification of the chemical composition of the plasma and possible contaminants.

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