Ionization of Helium Gas with a Tungsten Tip

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Abstract

The ionization of a helium atom was investigated as a function of gas pressure, with the use of a tungsten tip. The tungsten tip, to which the external voltage was applied, was used to generate a constant electron current. The ionization current of helium gas was measured as a function of gas pressure. Effective ionization occurred in the pressure range of 0.5-20 torr when the distance between the field emission tip and the collector was 1 cm. The ionization current was linearly proportional to the voltage that was applied to the tungsten tip.

Keywords: Ionization, Discharge characteristics, Field emission, Helium gas

1. Introduction

Gas discharge has long been an interesting subject. The Townsend model of dielectric breakdown was studied using photoelectron production at the cathode [1]. For low-pressure argon and nitrogen discharges, the electrical breakdown was investigated under the influence of an external longitudinal magnetic field, using Helmholtz coils [2]. For helium gas discharge, the ionization currents in helium between plane parallel silver electrodes were measured [3], and the breakdown in the low-pressure helium gas was investigated experimentally and by computer simulation [4]. Most general electron emission theories caused by temperature as well as an electric field have been studied to explain LCD backlighting [5]. It is important to understand the gas discharge in LCD backlights such as cold cathode fluorescent lamps (CCFLs) and hot cathode fluorescent lamps (HCFLs). Because the plane electrode method for gas discharge works only at a certain pressure, a tungsten tip was used to determine the gas discharge effect on a wide range of pressures.

In this paper, the ionization properties of helium gas were studied with the use of a tungsten tip. The ionization current of helium gas was measured as a function of pressure for a given voltage that was applied to the tungsten tip. The ionization current was also measured with the applied voltage at a constant pressure.

2. Theory

A tungsten tip is used as an electron source in a helium gas environment. When a high voltage is applied to the tungsten tip, the electric field of the tip can be approximated by [6]:

$$F \sim \frac{V}{5r}, \qquad \text{Eq. 1}$$

wherein F is the electric field of the tip, r is the radius of the curvature of the tip, and V is the voltage that is applied to the tip.

Due to the high electric field, the electrons in the tungsten tip can tunnel into the vacuum. This is called Fowler-Nordheim tunneling. The current density of the electron emission from the field emission tip is computed as follows [7]:

$$J_F = \frac{e}{2\pi h} \frac{\sqrt{E_F}}{(\phi_w + E_F)\sqrt{\phi_w}} F^2 e^{-8\pi\sqrt{2m\phi_w{}^3}/3hF}, \qquad \text{Eq. 2}$$

wherein E_F represents the Fermi energy, h is the Plank constant, ϕ_w is the work function, and m is the mass of the electron. The current density of the field emission depends mainly on the electric field and the work function of the tip.

Manuscript received February 2, 2009; Revised March 1, 2009; accepted for publication March 20, 2009.
The authors thank Jieping Fang for helping with the experimental set-up for this study, and Isaac F. Silvera for his helpful contributions to the discussion of the results.
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The Townsend discharge is a gas ionization process wherein an initially very small amount of free electrons, accelerated by a sufficiently strong electric field, gives rise to electric conduction through a gas via avalanche multiplication. When the number of free electrons drops or when the electric field weakens, the phenomenon ceases. The ionization process depends mainly on the applied electric field.

When an external voltage is applied to a tungsten tip, the electrons tunnel from the tungsten tip and are accelerated by the electric field between the tip and the collector. The accelerated electrons, which collide with the helium atoms, ionize the helium atoms. The main ionization process is described as follows:

$$\mathrm{e} + He \rightarrow \mathrm{e} + He^{+} + \mathrm{e}, \qquad \text{Eq. 3}$$

wherein the ionization potential of a helium atom is 24.6 V, which is the highest among atoms.

When the density of helium gas is low, the ionization process is also low because there are few helium atoms to ionize. When the density of helium gas is high, the electron energy is not big enough to ionize other helium atoms. Thus, the efficiency of the ionization depends on the density of the helium gas.

3. Experimental Setup

Initially, a field emission tip made of tungsten was tested in a vacuum. At the start of the test, the tungsten tip required a higher voltage to emit electrons. After it was trained a couple of times, it showed the same critical voltage as that needed to generate electron emission in a vacuum.

Fig. 1 shows the schematic diagram of the experimental apparatus. A 100-GΩ resistor was used to reduce the field emission current that went through the tungsten tip and to protect the tip from Joule heating. The high voltage that went through the resistor was applied to the field emission tip. The distance between the field emission tip and the collector was 1 cm. The tungsten tip and the collector corresponded to a negative electrode and a positive electrode, respectively. The copper collector was installed to collect the current from the helium gas environment, and the current was measured using a 617 Keithley electrometer. By measuring the charges with an oscilloscope, it was found that the critical voltage for the field emission tip was -1,100 V, at which the electron emission started.

4. Results and Discussion

A field emission current occurs when the electrons from a tungsten tip tunnel into a vacuum due to the high electric field. An ionization current occurs when the accelerated electrons ionize helium atoms.

It was found that the electron current that was emitted from the tungsten tip was not constant but made pulses in a vacuum when the field emission charge was detected with an oscilloscope. The pulse appeared when the voltage that was applied to the tip was -1,100 V. The typical shape of the pulse is shown in Fig. 2 (c). The total charges in the pulse were measured with the following equation:

$$Q = \int I(t)dt\,, \qquad \text{Eq. 4}$$

wherein Q is the total number of charges and I is the current. The number of electrons per pulse was from about 10^5 to 10^8 electrons, depending on the voltage that was applied to the field emission tip. As the applied voltage was increased, the number of electrons per pulse also increased. The repetition rate of the pulses also increased as the applied voltage was increased.

The pick-up current was measured with a 617 Keithley electrometer in a vacuum as the voltage that was applied to the tungsten tip was increased. The pressure dependent of the pick-up current was negligible. The pick-up current was subtracted from our experimental data to get the ionization current.

The current was also measured with the use of an oscilloscope to see the current in short time scales. Fig. 2

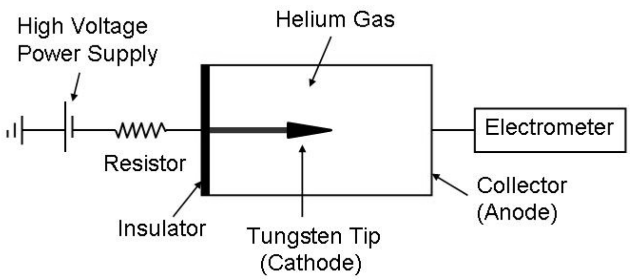

Fig. 1. Apparatus for measuring helium ionization. To protect the tungsten tip from ohmic heating, a 100-GΩ resistor was connected to the field emission tip. A collector made of copper was used to measure the current with an electrometer. The tungsten tip and the collector corresponded to the negative electrode and the positive electrode, respectively. The distance between the field emission tip and the collector was 1 cm.

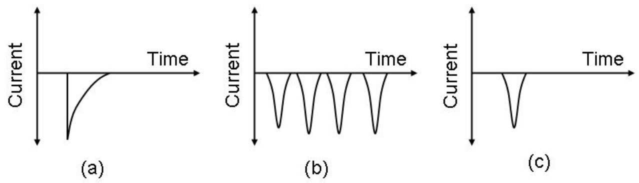

Fig. 2. Typical shapes of pulses from a tungsten tip. (a), (b), and (c) represent the typical shapes of a pulse at 500, 3, and 0.001 torr, respectively. The pulses were measured with an oscilloscope when the voltage that was applied to the tip was -1,200 V. The asymmetrical shape of the pulse in (a) shows that the electrons that were emitted from the tip collided much with the helium atoms due to the high pressure. The many symmetrical shapes of the pulses in (b) show that the electrons that were emitted from the tip ionized the helium atoms very efficiently, and the symmetric shape of the pulse in (c) shows that the electrons that were emitted from the tip did not ionize the helium atoms much due to the low density of helium gas, even when the electron energy was high enough to ionize helium.

shows the typical shapes of the pulses from a tungsten tip. Fig. 2 (a), (b), and (c) represent the typical shapes of a pulse at 500, 3, and 0.001 torr, respectively. The pulses were measured with an oscilloscope when the voltage that was applied to the tip was -1,200 V. Negative charges were always detected with the oscilloscope in the experiment because the electrons flowed to the collector and the positive helium ions flowed to the tip. The asymmetrical shape of the pulse in Fig. 2 (a) shows that a group of electrons that were emitted from the tip collided a lot with the helium atoms due to the high pressure. The many symmetrical shapes of the pulses in Fig. 2 (b) show that the electrons that were emitted from the tip ionized the helium atoms very efficiently, while they were accelerated to the collector in the range of the pressure that was effective in the ionization process. The symmetrical shape of the pulse in Fig. 2 (c) shows that the electrons that were emitted from the tip did not ionize the helium atoms much due to the low density of helium gas, even when the electron energy was high enough to ionize helium.

The ionization current of helium gas was measured as a function of the helium gas pressure at room temperature when the voltage that was applied to the tungsten tip was -1,200 V. Fig. 3 shows that the ionization current was measured as a function of the helium gas pressure with the use of the electrometer. The tungsten tip and the collector corresponded to the negative electrode and the positive electrode, respectively. When the helium ionization occurred as shown in Eq. 3, the positive current of the helium ion flowed to the tungsten tip and the negative current of the electrons flowed to the collector. A high current was detected in the pressure range of 0.5-20 torr, wherein the distance between the field emission tip and the collector was 1 cm. The ionization current started with the electrons that were emitted from the field emission tip and depended on the helium gas pressure. This shows that the electrons that were emitted from the field emission tip ionized helium gas most efficiently in the pressure range of 0.5-20 torr.

For the plane-parallel electrode arrangements, Paschen's law states that the breakdown characteristics of a gap are functions of the product of the gas pressure and the gap length, which is usually written as V = f(pd), wherein p is the pressure and d is the gap distance [8]. In that regime, the electrons have enough energy to ionize the gas atoms. The secondary electrons thus produced can also obtain a sufficient amount of energy from the electric field to ionize atoms and produce new electrons [2]. This gives rise to an avalanche-like growth of the degree of ionization. Both the (pd)min value, wherein the minimum is found, and the minimum breakdown voltage are characteristic of the gas and the cathode material. Penning found the values of 1.8 torr cm [9] and Hartmann 4.1 torr cm [4] for (pd). In this

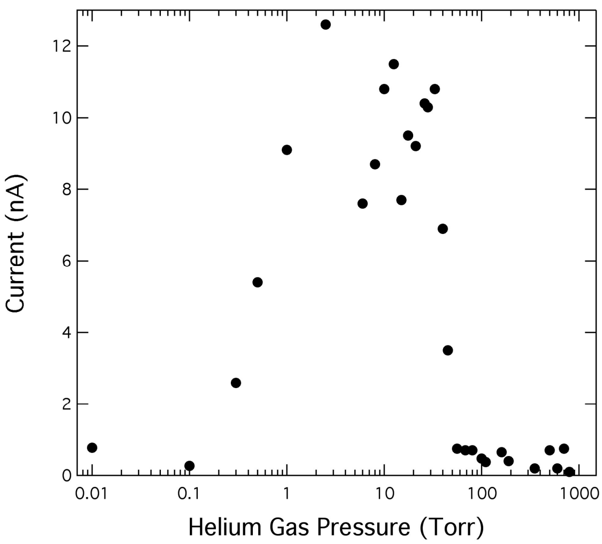

Fig. 3. The current is measured as a function of helium gas pressure. The voltage that was applied to the tungsten tip was -1,200 V. The high current, which corresponds to the efficient ionization of helium atoms, was detected in the pressure range of 0.5-20 torr, wherein the distance between the tip and the collector was 1 cm. The highest current represents the most efficient ionization of helium gas.

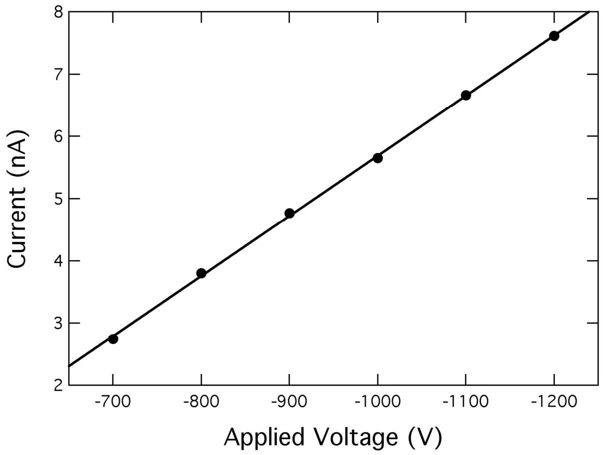

Fig. 4. The current is measured as a function of the applied voltage. The pressure of helium gas is 3 torr. The magnitude of the current corresponds to the efficiency of helium ionization. The line in the figure came from the linear fitting of the data. The ionization current of helium gas linearly increased as the voltage that was applied to the cathode increased.

study, such values were found between 0.5 and 20 torr cm, which is consistent with the results of previous experiments.

Fig. 4 shows that the current is measured as a function of the applied voltage. The ionization current is measured at the pressure of 3 torr, which is in the range of the most effective ionization. The electric field between the tip and the collector increased as the voltage that was applied to the cathode was increased. The current measured in Fig. 4 came mainly from the ionization of helium, because the field emission current from the tip was below nA in the range of the voltage that was applied to the tip. The ionization current linearly increased as the voltage that was applied to the field emission tip was increased. The ionization effect was not found in the pressure values outside 0.5-20 torr.

This research is useful in understanding the ionization of gas in a field emission lamp, and the discharge characteristics of a cold cathode fluorescent lamp and a hot cathode fluorescent lamp.

5. Conclusions

The ionization efficiency of helium gas was shown as a function of pressure and applied voltage, with the use of a tungsten tip. The effective ionization of helium gas occurred in the pressure range of 0.5-20 torr when the distance between the tip and the collector was 1 cm. The ionization current of the helium atom linearly increased with the increase in the voltage that was applied to the cathode.

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