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Effect of negative ions on the characteristics of plasma in a cylindrical discharge

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Abstract

The effect of negative ions on the density, temperature, and potential of plasma in a direct current discharge regime has been studied experimentally. Nitrogen as an electronegative gas was used to produce negative ions in the plasma. Langmuir probe was employed to measure plasma parameters. Discharge was performed in an evacuated glass tube, with circular disk electrodes at different pressures. To obtain the spatial variation of plasma characters, measurements were done at different points on the axis of discharge tube. Argon and nitrogen gases were used as the working gas, and plasma current was kept constant at 5 mA during the experiments. Discharge voltage decreased sharply with increasing pressure for both argon and nitrogen plasmas; however, to sustain the discharge at constant current in nitrogen plasma, higher voltage was required in comparison with argon plasma. The plasma electron density was decreased from cathode to anode during the discharge process, while electron temperature was increased. Results confirm that nitrogen plasma contains negative ions, and discharge process is influenced by them noticeably.

Keywords: Plasma; Discharge; Langmuir probe; Electron density; Electron temperature; Electronegative

Introduction

Classical low-pressure electrical discharge has been the topic of several researches in the field of plasma physics for many years [1-3]. Recently, the development of plasma technology in the industry has motivated plasma physicist to focus their researches on different phenomena that occurred in the electrical discharge tube at a wide variety of discharge conditions. Thin film deposition, surface etching of materials, and plasma sterilization are some important samples of the application of plasma in the industry [3-5]. Using different working gases in the discharge process motivated us to study and compare the characteristics of nitrogen and argon plasmas in a similar discharge current and pressure. Nitrogen is one of the most electronegative elements in the periodic table. Thus, in the case of nitrogen plasma, we have also negative ions in the discharge tube. In contrast, argon plasma consists of electrons and positive ions besides neutral particles. This fact is the start point of several observed differences during the discharge process in these two kinds of plasmas.

We attempt to experimentally investigate the influence of pressure on plasma characteristics via the Langmuir probe (LP) technique. Measurements were done using a single Langmuir probe. This kind of probe is capable of measuring the temperature and density of plasma as well as the plasma potential. Besides, we obtain more information from the plasma using the floating potential of the probe [6].

This manuscript is organized as follows: Following the section 'Introduction,' the 'Experimental setup' is explained. The 'Results and discussion' and 'Conclusion' are also presented.

Experimental setup

The experimental setup consists of an evacuated glass tube with circular plane disk electrodes, which is illustrated in Figure 1. The gap between electrodes was 18 cm. Cathode was connected to a high-voltage direct current (DC) power supply, and anode was grounded. In this geometry, plasma can be assumed to be cylindrically symmetric. Tube was evacuated down to 6.2×10^{-5} mbar by a turbo molecular pump backed by a rotary pump. During the first experiment, argon was used as the working gas, and for the second experiment, nitrogen

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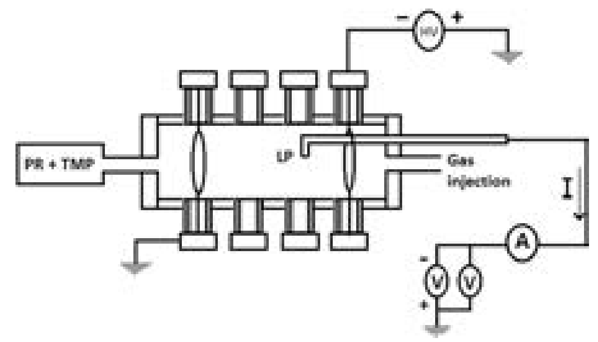

Figure 1 Discharge tube with LP circuit.

was introduced into the system under continuous pumping condition at working pressures of 1×10^{-2}, 1.9×10^{-2}, 3×10^{-2}, 4×10^{-2}, and 5.4×10^{-2} mbar. The experiments were performed at constant current mode equal to 5 mA. In fact, at each pressure of the discharge tube, we let self-sustaining discharge voltage changed such that the discharge current remains constant. Discharge voltage was measured by a high-voltage probe connected between the cathode and the earth. Plasma current was obtained by measuring the potential difference of a 10-kΩ resistor which was between the high-voltage power supply and cathode.

To determine the plasma parameters, a movable single LP was designed and constructed. The probe was made of a narrow quartz pipe with cylindrical tungsten tip. The length of the probe tip was vertically 10 mm, and its radius was 0.3 mm. The probe could be moved longitudinally along the tube axis (*z*-axis). The probe was connected through a simple electrical circuit to a DC power supply ranging from −50 to 50 V with respect to the ground.

To measure the plasma parameters, the probe was positioned at six axial points, which are indicated in Figure 1. The location of the point from the cathode is $z = 1$ cm, and $z = 16$ cm is closed to the anode. The plasma parameters (electron density, electron temperature, and plasma potential) were obtained by analyzing the current–voltage characteristic curve of the probe.

Results and discussion

The discharge voltage as a function of pressure for two cases of argon and nitrogen plasmas is presented in Figure 2. The discharge voltage was decreased with increasing pressure of the working gas in the discharge tube while the plasma current was kept constant. In fact, by increasing the discharge pressure, the plasma conductivity was increased. In plasma, the electrical current is carried by both ions and electrons. For a Lorentzian plasma in which the accelerated electrons toward the anode collide repeatedly with the neutral background gas, the electrical conductivity σ is given by microscopic parameters of the plasma:

$$\sigma = \frac{e^2 n_e}{m_e \nu}, \tag{1}$$

in which m_e and e are the electron mass and electric charge, respectively, n_e is the plasma electron density, and ν is the collision frequency between plasma electrons and neutral particles [2,3]. By increasing the working pressure in the discharge tube, the electron density increases. Of course, by increasing the working pressure, the collision frequency will also increase. However, it can be observed that in this regime of electrical discharge, increasing the plasma electron density is the predominated process that leads to increasing plasma conductivity.

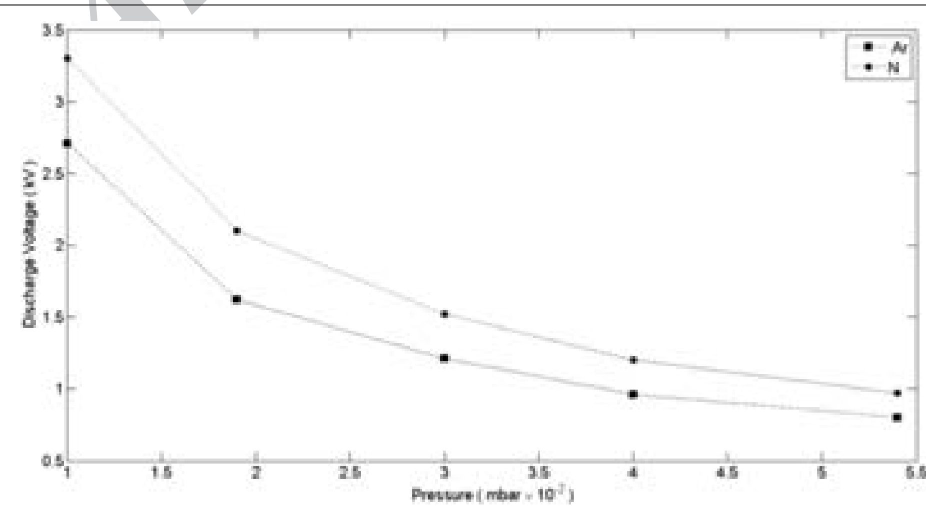

Figure 2 Discharge voltage as a function of working gas pressure.

Figure 3 **Plasma and Langmuir probe in the discharge tube close to the cathode.**

Nitrogen is an electronegative gas. Using nitrogen as the working gas, we have negative ions as well as positive ions in the plasma medium, so the electron density of nitrogen should be smaller than the electron density of argon plasma in a similar situation. In this case, the conductivity of nitrogen plasma is smaller than the conductivity of argon plasma, so a larger discharge voltage is required to sustain the plasma with similar current in the tube. Similar results are obtained by Yasserian et al. [7]. They used different percentages of oxygen in their reactor to produce negative ions.

The image of discharge tube with nitrogen plasma is shown in Figure 3. Several discharge regions can be observed in the discharge tube. Cathode surface was always luminous due to high-energy ion impact, and immediately in front of the cathode, the cathode glow region can be observed. After the cathode glow region, a dark region is formed. This region is known as Crookes dark space beside the cathode region [2-4]. By increasing the pressure of the tube, the length of cathode region was decreased while the length of negative glow region was increased as is shown in Figures 4 and 5, respectively, for both nitrogen and argon plasmas. Cathode region consists of low-energy electrons which are unable to ionized or excite neutral particles. By increasing the pressure in the discharge tube, the number of electrons and collisions increases, which leads to increasing number of ionization and excitation. In this case, the length of negative glow region will increase while the length of cathode region decreases [7,8]. Since nitrogen is an electronegative gas, nitrogen plasma contains negative ions. In this case, the number of electrons in nitrogen plasma is smaller than argon plasma, so the length of cathode region will be larger while the length of negative glow region is smaller than argon plasma. Because of the thickness of the LP tube, we could not measure plasma parameters in the cathode glow regions, and in the cathode dark space, the current of the probe was 0 for the voltage interval of −50 to +50 V.

In Figure 6a,b, variation of plasma electron density along the discharge tube at different discharge pressures for argon and nitrogen plasmas is presented, respectively. Also, in Figure 7a,b, the temperature of plasma electron at these points can be observed. From cathode to anode, the density of electrons was decreased while their temperature was increased. Drifting from cathode to anode, electrons achieve energy from the applied electric field which leads to the increase in their temperature. By increasing the temperature, the density decreases. Collision is another noticeable point. Increasing plasma density collisions leads to the decrease in temperature of plasma electrons. Because of the collision, the energy of electrons transfer to ions and neutral particles, so we will

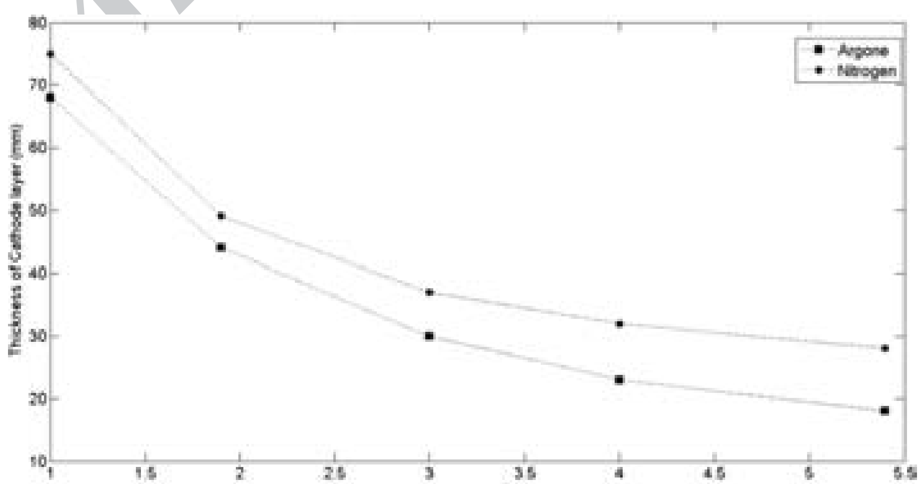

Figure 4 **Thickness of the cathode layer region versus pressure in the discharge tube.**

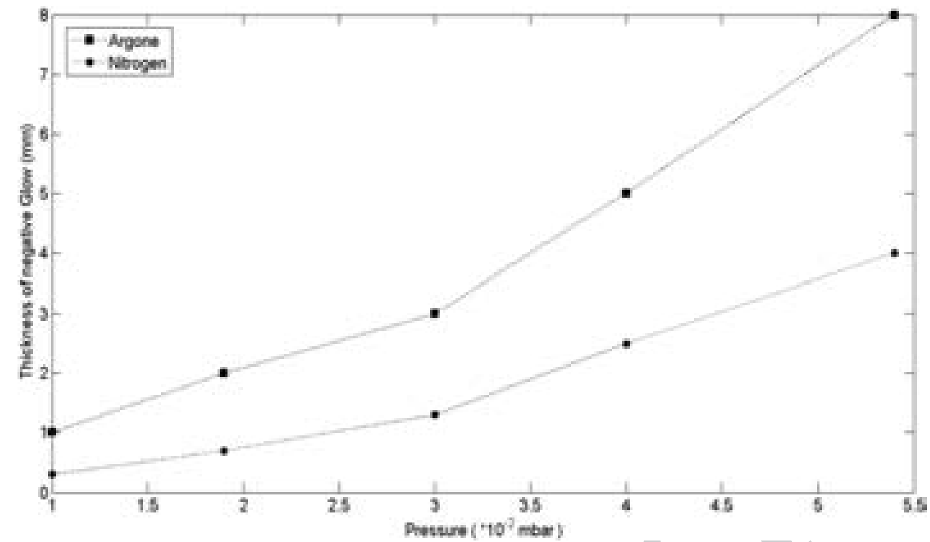

Figure 5 Thickness of the negative glow region versus pressure in the discharge tube.

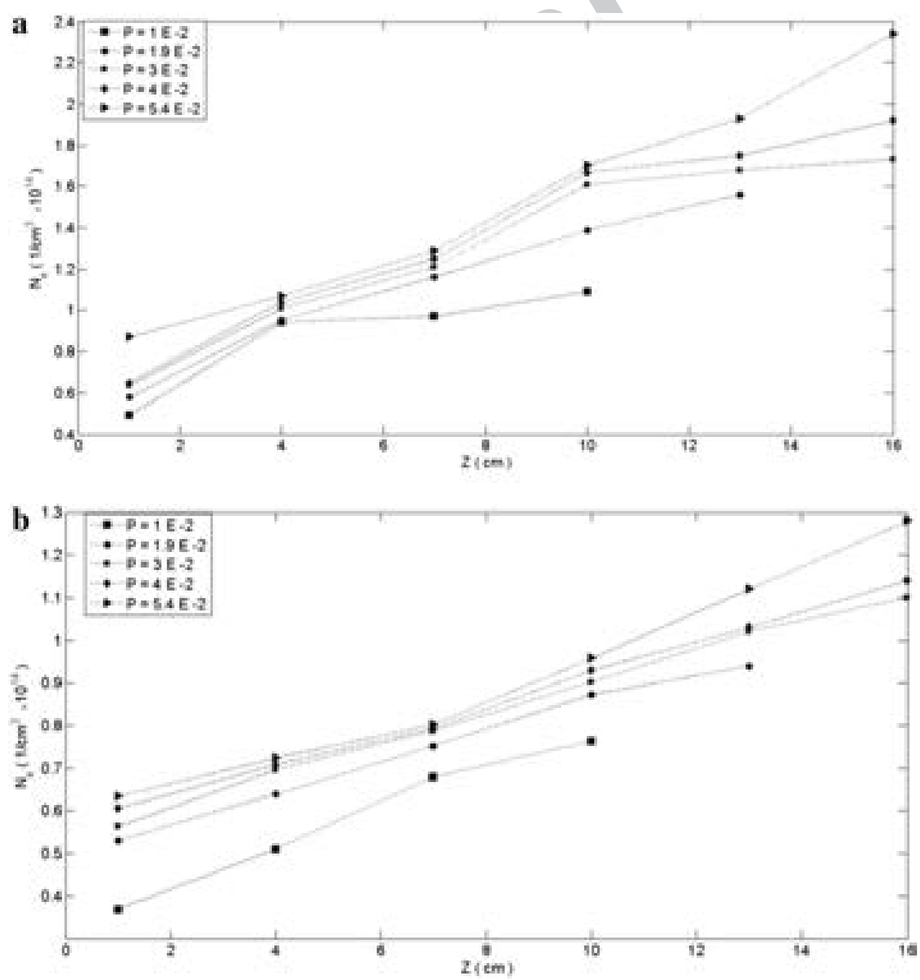

Figure 6 Plasma electron densities along the discharge tube. At different pressures in argon **(a)** and nitrogen **(b)** plasmas.

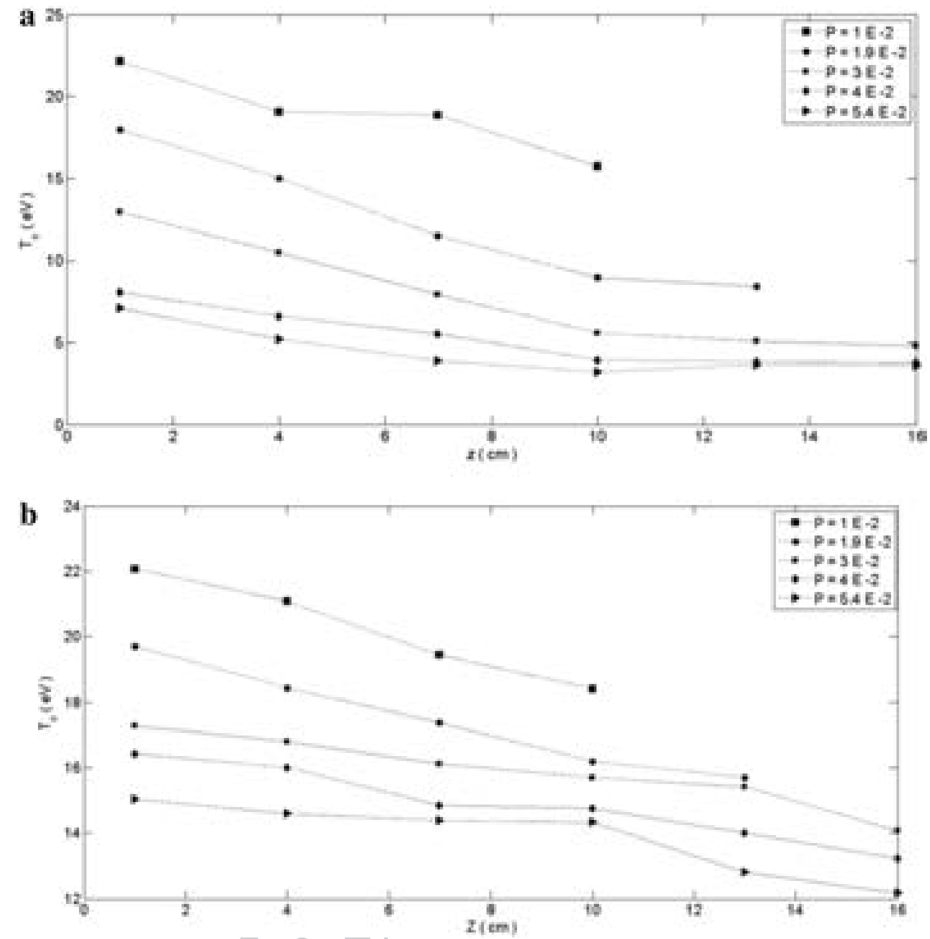

Figure 7 Plasma electron temperatures along the discharge tube. At different pressures in argon **(a)** and nitrogen **(b)** plasmas.

have colder electrons [7]. After introducing nitrogen as an electronegative gas, the electron density is decreased while the electron temperature is increased in comparison with argon plasma [9-11]. Plasma current is kept constant in both argon and nitrogen plasmas. However, in nitrogen plasma, some electrons are bonded to nitrogen atoms to make negative ions. Because plasma is quasineutral, the number of electrons in nitrogen plasma is decreased. Decreasing the density of electrons leads to the decrease in the collision number, so in the case of nitrogen plasma, electron energy is higher.

Variation of the floating potential in the discharge tube for both cases of argon and nitrogen plasmas is shown in Figure 8a,b. Floating potential is the potential at which the current of LP is 0. In this experiment, the floating potential was increased from cathode to anode. Increasing the floating potential shows an increase in the number of electrons in the Debye sphere [12]. The number of electrons in the Debye sphere can be indicated by the following relation:

$$N_D \sim T^{3/2}/{n_0}^{1/2} \qquad (2)$$

in which N_D is the number of electrons in the Debye sphere and T and n_0 are the temperature and plasma electron density, respectively [2]. As was shown in Figures 4 and 5, the discharge tube electron temperature was increased from cathode to anode while electron density was decreased. Consequently, the floating potential increases from cathode to anode. In the case of nitrogen plasma, we have less number of electrons in the Debye sphere, so a smaller probe voltage is required to stop the probe current. From cathode to anode, firstly, the floating potential increases, i.e., the number of electron decreases (such as argon plasma). This is the effect of negative cathode repulsive force on electrons. However, after achieving a maximum, the floating potential of nitrogen plasma decreases. This can be explained by the rate of variation of temperature and density in the argon

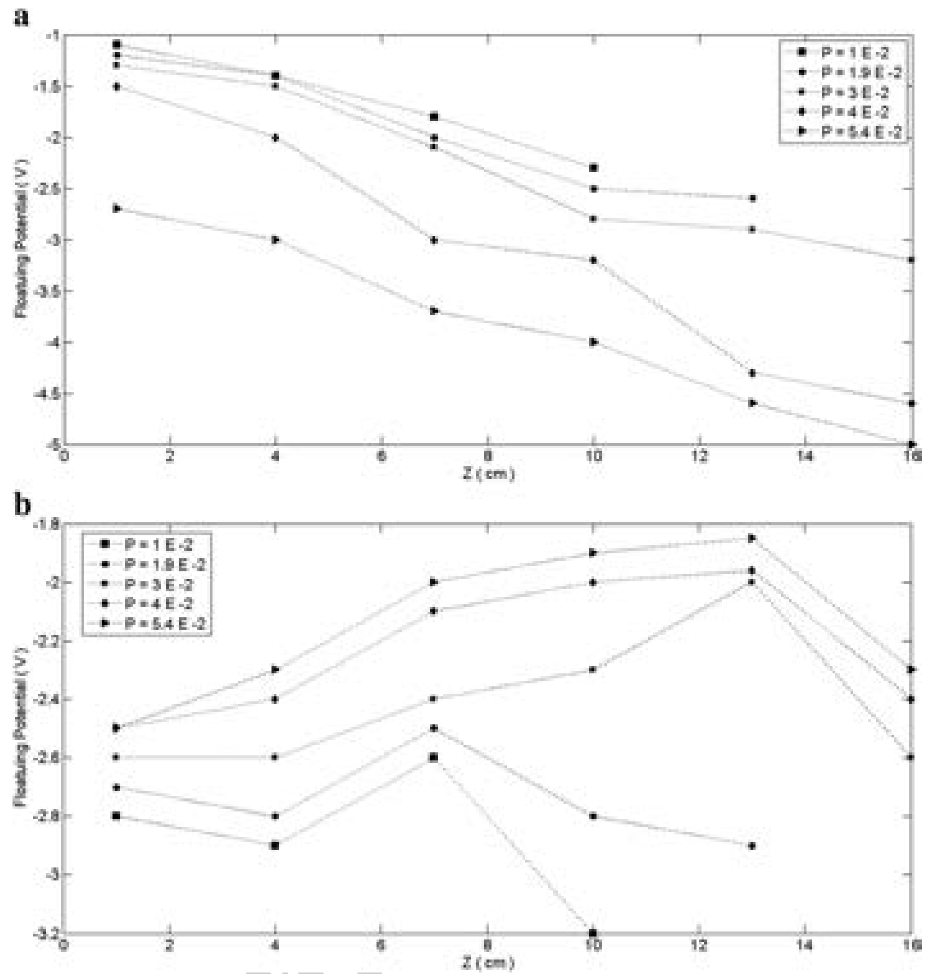

Figure 8 Floating potentials of argon (a) and nitrogen (b) plasmas. Along the discharge tube on plasma axis at different pressures.

and nitrogen plasmas. The rate of decreasing the density and temperature from cathode to anode is smaller in the nitrogen plasma in comparison with the argon plasma. This is the effect of higher temperature of electrons in the nitrogen plasma.

Variation of plasma potential V_p on the axis of discharge tube is presented in Figure 9a,b for argon and nitrogen plasmas, respectively. The plasma potential is the potential of the plasma with respect to the walls of the device at a given location in the plasma. Generally, the walls of discharge tube are at negative potential due to runaway electrons of plasma. Thus, V_p is generally a few volts positive with respect to the walls. The plasma potential is inferred from the intersection of two tangent lines to the curve $\ln(I_{probe})$ versus V_{probe} for $V_{probe} > V_p$ and $V_{probe} < V_p$ [13]. The plasma potential of both argon and nitrogen plasmas increases on the axis of discharge tube from cathode to anode as is shown in Figure 9. The reason can be due to decreasing electron density from cathode to anode. In the case of nitrogen plasma, electron density on the axis is smaller, so we have a larger plasma potential on the axis of discharge tube than the other regions.

Conclusions

Different characters of argon and nitrogen plasmas in a DC discharge tube are studied experimentally via the Langmuir probe technique, and results are compared. The effect of nitrogen as an electronegative gas is investigated in different parameters of plasma such as temperature, density, and potential. All results confirm that because of the presence of negative ions in nitrogen plasma, the number of electrons is smaller in this case, which leads to the increase in discharge voltage of nitrogen in comparison with the argon plasma. The electron density number becomes smaller while the electron

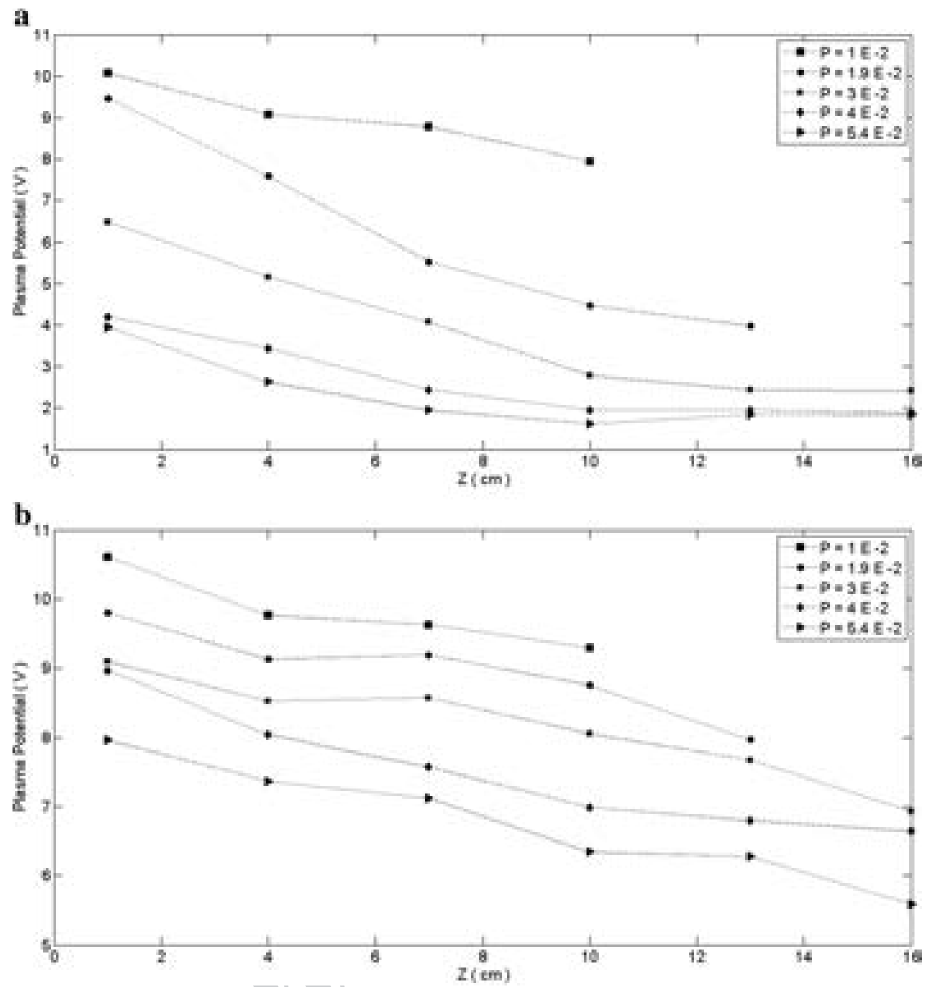

Figure 9 Plasma potentials at different points of the discharge tube. In argon **(a)** and nitrogen **(b)** plasmas at different pressures.

temperature becomes larger with increasing electronegativity of the working gas of plasma. Using more electronegative gas for generating plasma leads to increasing plasma conductivity. In the case of nitrogen plasma, we have a peak in the floating potential diagram which is the result of higher electron temperature. In fact, the number of particles in the Debye sphere has a maximum in a discharge tube. The thicknesses of negative glow and cathode layer regions in the discharge tube at different pressures were measured and compared in the case of argon and nitrogen plasmas. Results show that because of the smaller number of electrons in the nitrogen plasma, the thickness of cathode glow region is larger while the thickness of negative glow region is smaller. Similar results are presented in other works [7,14]. In [7], the authors have changed the percentage of additional oxygen to working gas in order to change the electronegativity of the system. In [14], others have investigated the effect of input power on the plasma discharge. In both researches, the effect of electronegavity and negative ions on the behavior of plasma is similar. Decreasing the electron density leads to increasing resistivity, so in the constant current regime of plasma discharge, the discharge voltage will decrease. Using an electronegative gas leads to decreasing electron temperature.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
FA and DD participated equally in preparing the experimental setup, doing the experiments, and preparing the manuscript. Both authors read and approved the final manuscript.

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