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Experimental study of the influence of nitrogen admixture on characteristics of DC glow discharge in He gas

O. F. Farag and M. M. Mansour

Zagazig University, Faculty of Science, Physics Department, Zagazig - Egypt

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ABSTRACT

The influence of nitrogen admixture on the characteristics and various plasma parameters in DC He discharge at low pressure was studied experimentally. It was shown that the addition of nitrogen leads to noticeable increase in discharge current at the same discharge voltage and gas pressure. Contrary, the breakdown voltage and the cathode fall thickness were observed to decrease with the addition of nitrogen. Single Langmuir probe measurements for determination of plasma parameters (electron energy distribution functions, electron temperature, ion density and electron density) in He and (He-N_2) gases were performed and explanation of observed effects were given.

Key words: Glow discharge/ (He-N_2) Gas mixture/ Breakdown voltage/ cathode fall thickness/ Langmuir probe.

INTRODUCTION

Glow discharges are used in a range of application fields: in the microelectronics industry for thin film deposition and plasma etching, as plasma display panels, as metal vapor ion lasers, as fluorescent lamps, and also in analytical chemistry [1].

A glow discharge is characterized by its distinctive regions between the cathode and the anode electrodes across the tube. The physical characteristics of these regions depend on the parameters of the discharge that is, geometry of the discharge tube, pressure of the working gas, type of gas, cathode material, applied potential and the discharge current[2].

It is known that an addition of molecular admixture to rare gas leads to changing of electrical and spectral characteristics of glow discharge [3]. The nature of changes depends on conditions (sort of rare gas and admixture, percentage of admixture, gas pressure and so on). For example, in the case of He and Ne the addition of small percentage of molecular gas can lead to the decrease in both, breakdown voltage and steady state discharge voltage.
The aim of the present work was to study the effect of the changes in N_2 percentage on the electrical characteristics (Parameters) of (He-N_2) mixture glow discharge and also, determine plasma parameters (electron density and temperature, electron energy distribution function and ion density) using single Langmuir probe technique at different N_2 percentage in (He-N_2) gas mixture.

MATERIALS AND METHODS

2.1) Plasma Source

Figure (1) shows a schematic diagram of the experimental setup. A cylindrical discharge cell made of a Pyrex glass tube of 18 cm length and 13 cm diameter. Two parallel movable circular electrodes were enclosed in the discharge cell. The two electrodes were made of stainless steel and each of them was 5 cm diameter. The discharge cell was evacuated using a gas rotary pump (*Edwards H. vacuum pump, model ED 200*) to a base pressure down to 10^{-3} torr.

The flow of helium and nitrogen gases is monitored with mass flow meters whereas pressure in the chamber is recorded by using pirani gauge. The applied voltage was controlled by a DC power supply which can produce potential up to 2000 V.

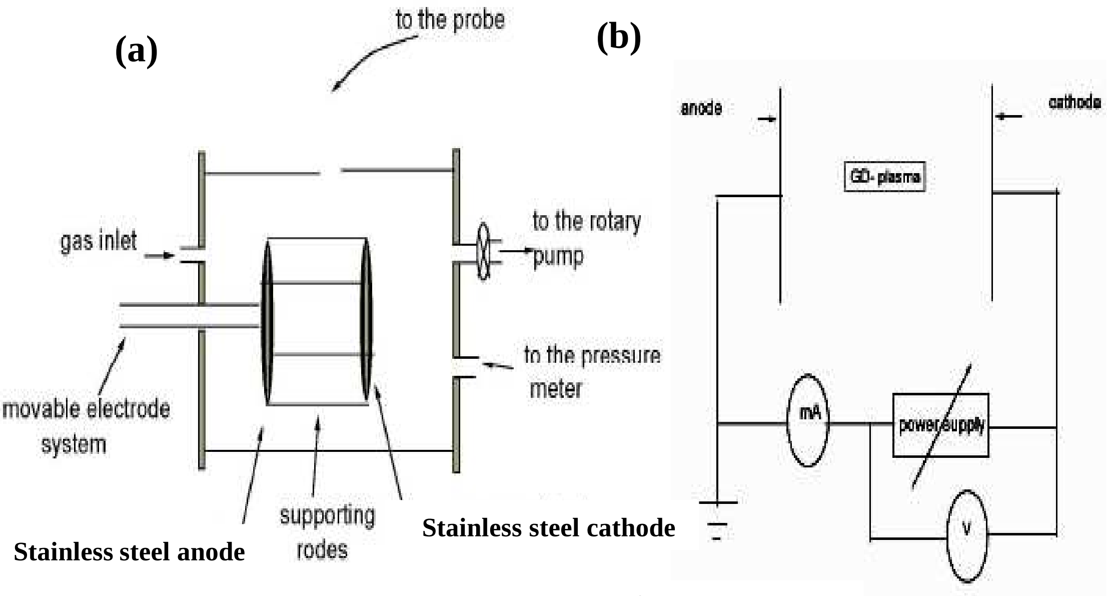

Figure (1) A schematic diagram for
(a) The experimental equipment and
(b) The electrical circuit

2.2) Langmuir Probe Measurements

Langmuir probe is commonly used as low-temperature plasma diagnostic due to its easy and simple implementation compared to other plasma diagnostics [4]. From the probe data it is possible to determine a large variety of parameters characterizing the plasma including electron density, electron temperature and ion density. The method of the Langmuir probe measurements is based on its *I*–*V* characteristic the so-called probe characteristic. The Langmuir probe assembly consists of Tungsten wire of 0.30 mm diameter and 5 mm length, supported by a Pyrex glass tube. Probe current is measured for DC bias voltages ranging from −100 to +100V.

The electron temperature, T_e, is determined in electron volt (eV) from the slope of the ln (*I*)–*V* curve of the probe in the transition region between floating potential and plasma potential by the following equation [5]:

$$T_e = e/k \quad d\ \ln\left(I\right)/dV \tag{1}$$

where *e* is the electronic charge, *k* is the Boltzmann constant, *I* is the electron current and *V* is the probe voltage.

The electron number density, n_e, in cm^{-3} is obtained from the electron saturation current (I_{Se}) using the following equation [5]:

$$n_e = \frac{4I_{Se}}{eA}\left[\frac{m_e}{2kT_e}\right]^{1/2} \tag{2}$$

where *A* is the probe area and m_e is the magnitude of electronic mass.

Assuming a Maxwellian energy distribution in the unperturbed plasma, the following simplified formula for a cylindrical prope may be used to determine the ion current in the OML regime [6]:

$$I_i = \sqrt{2}/\pi A e n_i \left(|eV|/m_i\right)^{1/2} \tag{3}$$

where I_i is the ion current and m_i is ion mass. The slope of the linear relationship of the square of ion current I_i^2 versus prope voltage yields the plasma ion density, n_i , without knowledge of the electron temperature, in accordance with OML theory.

The electron energy distribution functions, *EEDFs*, are also important for understanding various plasma processes, such as electron impact ionization and excitation. In this study the EEDFs are calculated according to Druyvesteyn formula [7]:

$$F(\varepsilon) = 2(2m_e)^{1/2}(e^3A)^{-1}V^{1/2}\frac{d^2I_p}{dV^2} \tag{4}$$

where I_p is the probe current.

The plasma electrical conductivity [8] is given by the following equation:

$$\sigma = \frac{e^2n_e}{m_e\nu_{en}} = \frac{e^2n_e}{n_g\sigma_{en}\sqrt{3m_ekT_e}} \tag{5}$$

where ν_{en} is the electron-neutral collision frequency, n_g is the neutral atom density and σ_{en} is the electron-neutral collision cross-section.

The neutral atom density, n_g, is computed from the gas pressure and temperature using ideal gas law ($n_g = P / kT_g$). The neutral gas temperature, T_g, in glow discharges has been studied previously by means of Doppler broadening, thermal couple and via a manometer probe [8]. Recently, Rayleigh scattering of laser radiation is used to measure the neutral gas temperature. In the present work T_g is ~ 350 K as measured using a thermal couple.

RESULTS AND DISCUSSION

3.1) Electrical Parameters

Figure (2) shows the (*I-V*) characteristic curves of He, at different N_2 percentage in (He-N_2) gas mixture where gas pressure is kept constant at 0.2 Torr. It is clearly seen that, at the same applied voltage and gas pressure, the discharge current increases by increasing the N_2 percentage in (He-N_2) gas mixture. This result is similar to that reported by Tsukiji et al. [9].

The increase in the discharge current by the increase of N_2 percentage in (He-N_2) gas mixture can be explained as follows: the Penning ionization processes $He^* + N_2 \rightarrow N_2^+ + He + e$ [3], since ionization potential of N_2 (15.78 eV) is lower than the energies of He^* (19.82 and 20.62 eV) metastable states [9]. Also, helium has lesser electron collision cross-section than nitrogen [10], thus an increase in the number of nitrogen molecules and atoms in the mixture, increase the probability of direct ionization of molecules and atoms by electron impact [3, 11].

The breakdown voltages were measured at different N_2 percentage in the (He-N_2) gas mixture and in the pressure range of 0.04 to 1 torr with the inter-electrode distance fixed at 7 cm (Figure 3). From the figure we can notice that, the breakdown voltage decreases by increasing N_2 percentage in (He-N_2) gas mixture. This can be attributed to the lower ionization potential of nitrogen as compared to helium [12]. Also it has been found that, the breakdown voltages in (He-N_2) gas mixtures lie between those of the constituents. This result is similar to that explained by [13].

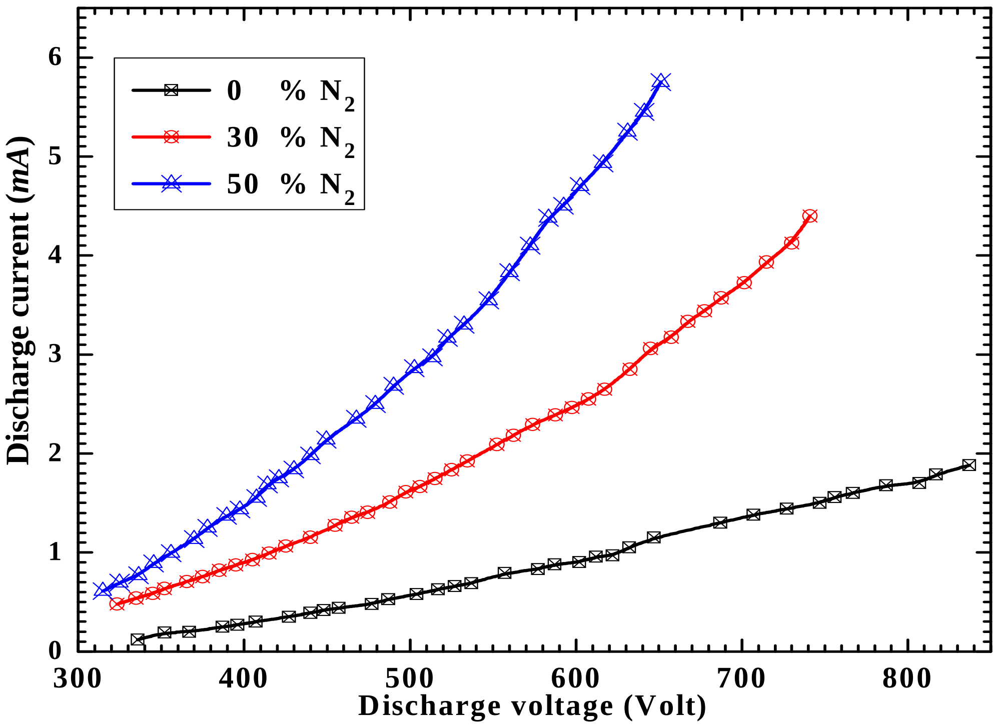

Fig. 2: The I-V characteristic curves of He, at different N_2 percentage in (He-N_2) gas mixture and P = 0.2 torr.

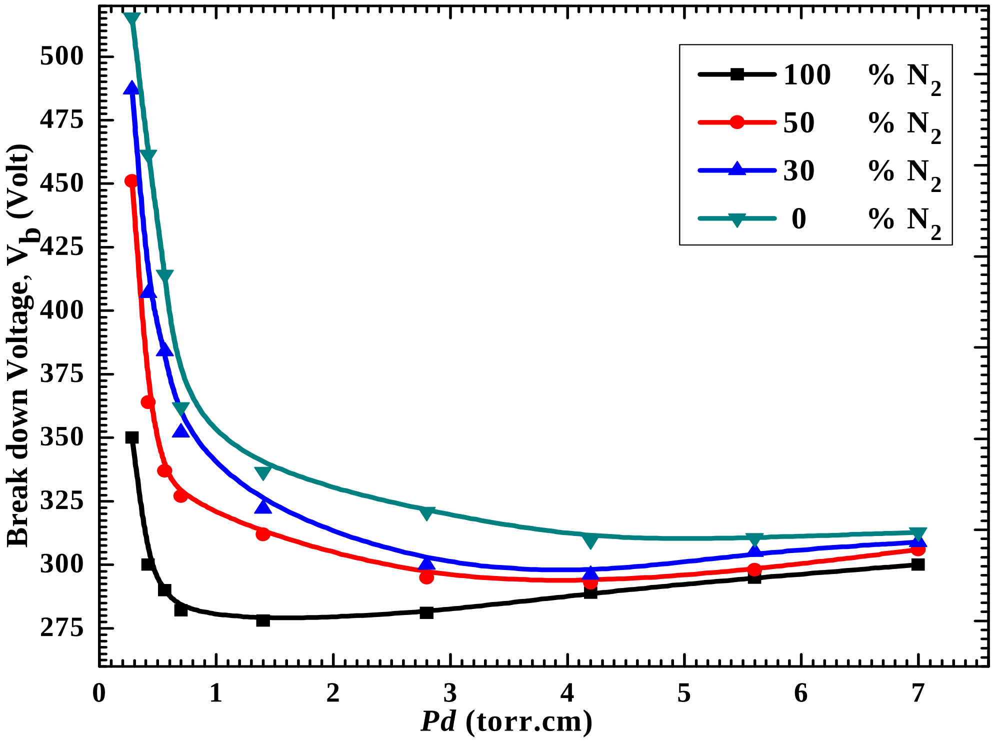

Fig. (3) Paschen's curves of He, at different N_2 percentages.

Figure (4) shows the cathode fall thickness, as a function of N_2 percentage in the (He-N_2) gas mixture. The cathode fall thickness (d_c) decreases by increasing percentage of N_2 in the gas mixture. The decrease in d_c as N_2 percentage in the (He-N_2) gas mixture increases can be attributed to the increase in the ionizing collision frequency and hence the discharge needs less distance to create the negative glow region.

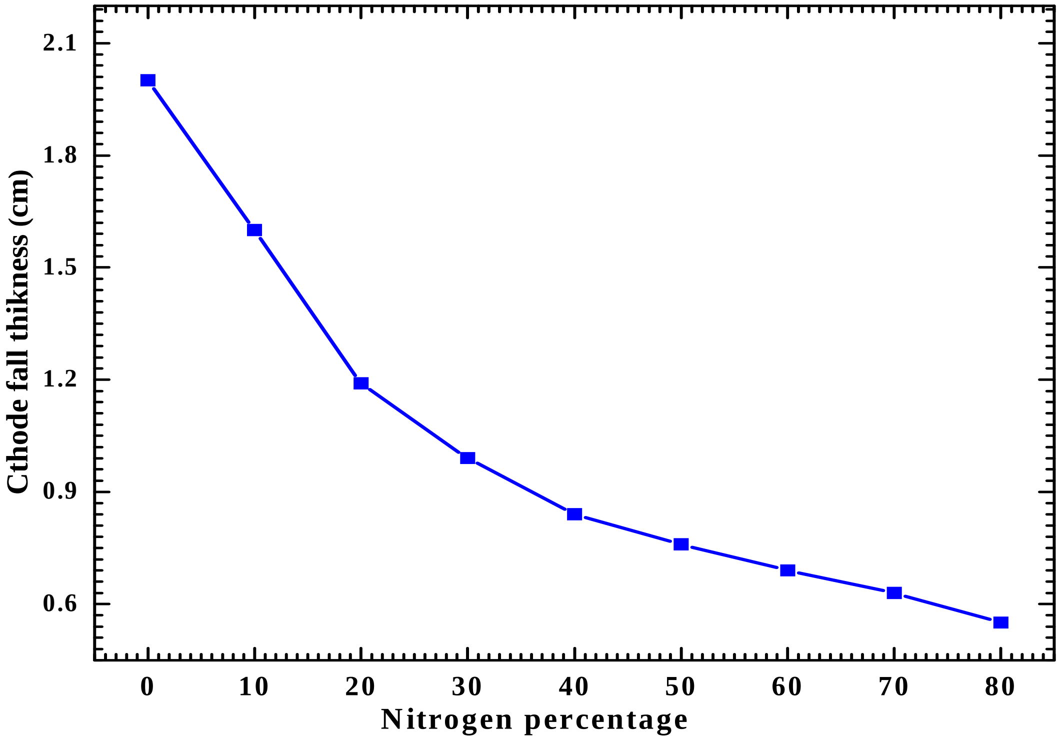

Fig. 4: The cathode fall thickness (d_C) as a function of N_2 percentage in the mixture with 0.2 torr filling pressure at 550 V DC discharge.

3.2) Plasma properties

Figure 5 shows the axial distribution of the electron temperature, in He plasma when the concentration of N_2 in (He-N_2) gas mixture is varied. It is obvious that as the N_2 concentration in (He-N_2) gas mixture is increased, T_e decreases. This result agrees with the results of papers [14, 15, 16].

The decrease of electron temperature in He plasma with the increase of nitrogen percentage in the mixture may be explained as follows: helium has lesser ionization cross-section than that of nitrogen so nitrogen addition increases the probability of inelastic collisions of electron and hence there is decrease in effective electron temperature [14].

Figure 6 shows the axial distribution of the electron number density, in He plasma when the concentration of N_2 in (He-N_2) gas mixture is varied. It is clearly seen that, the electron number density increases by increasing N_2 percentage in gas mixture. This can be attributed to the Penning ionization processes and higher ionization cross-section of nitrogen than that of He.

Figure 7 shows the axial distribution of the ion number density, in He plasma when the concentration of N_2 in (He-N_2) gas mixture is varied. The effects of the gas admixing show the same tendency as the electron number density since plasma is quasi neutral.

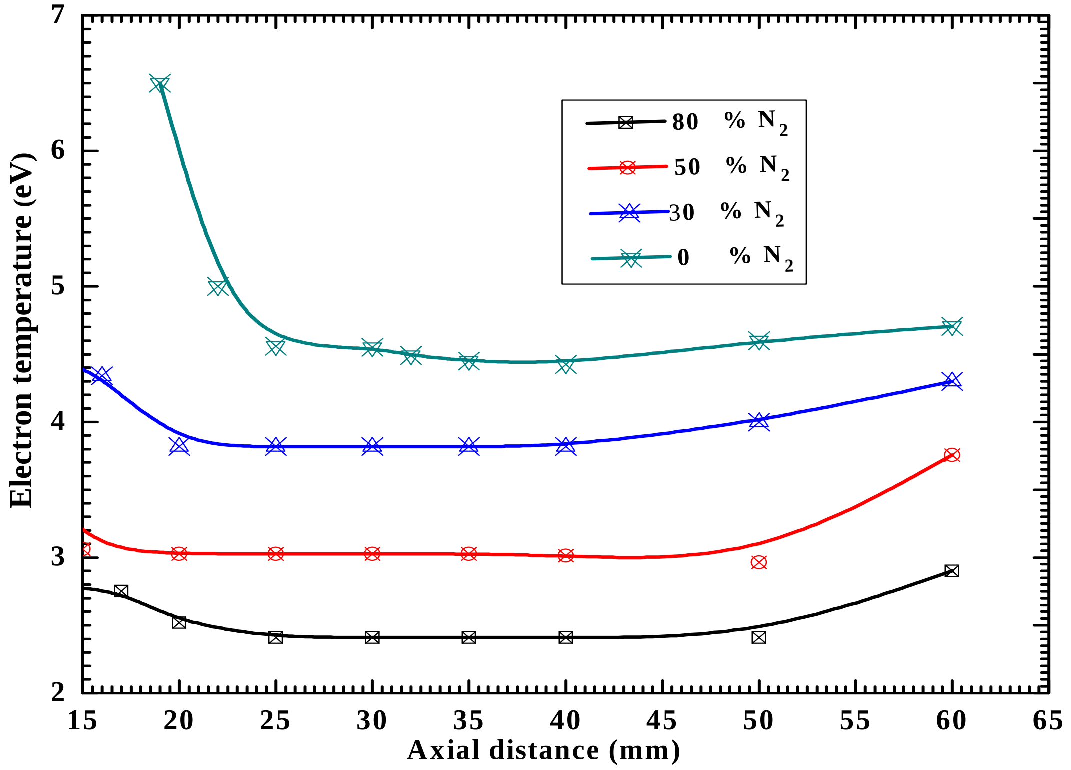

Fig. 5: The axial distribution of the electron temperature in He plasma, at different N_2 percentage in the mixture with 0.2 torr filling pressure at 550 V DC discharge.

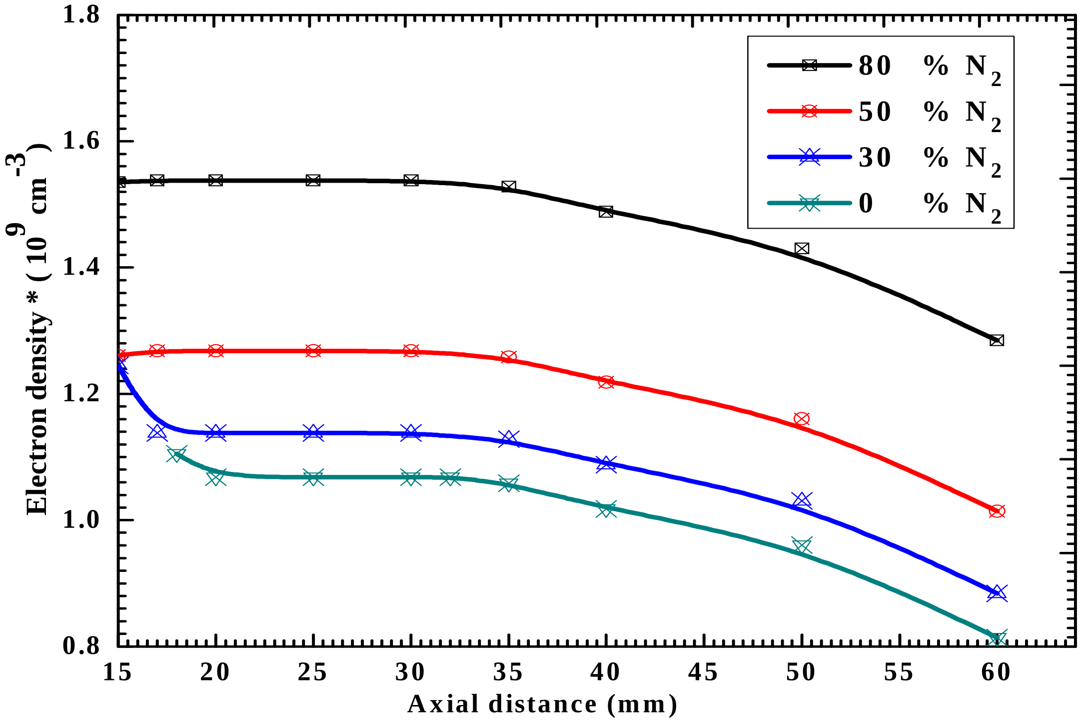

Fig. 6: The axial distribution of the electron number density in He plasma, at different N_2 percentage in the mixture with 0.2 torr filling pressure at 550 V DC discharge.

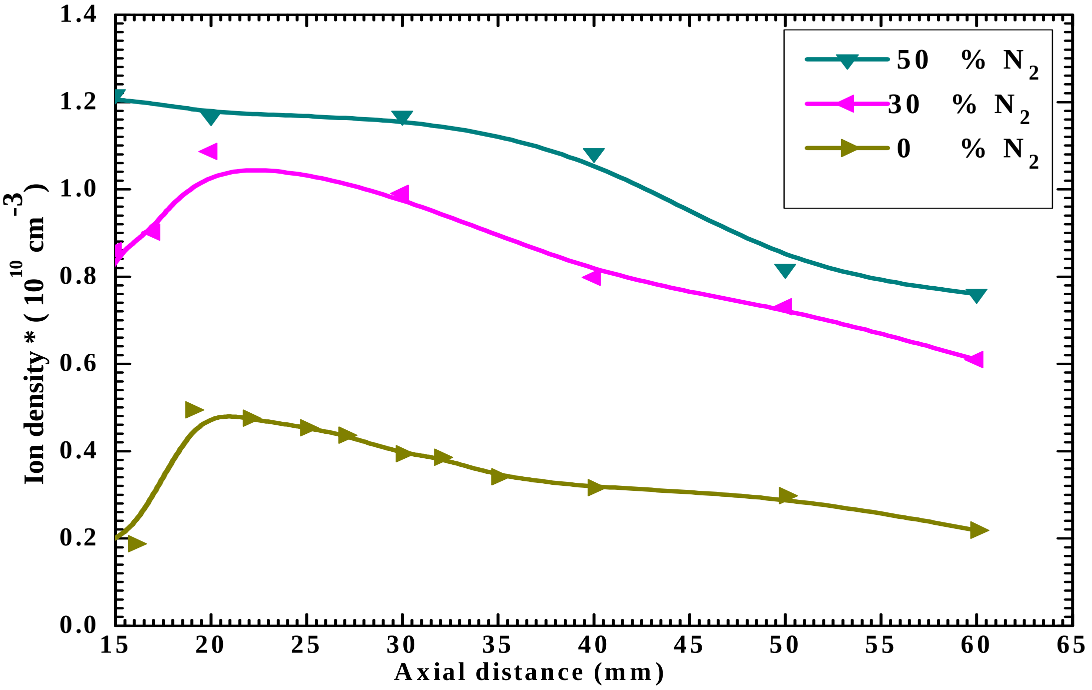

Fig. 7: The axial distribution of the ion number density in He plasma, at different N_2 percentage in the mixture with 0.2 torr filling pressure at 550 V DC discharge.

Figure 8 shows the measured electron energy distribution function (*EEDFs*) as a function of N_2 gas mixing ratio in He plasma. The plots indicate that (*EEDFs*) have two peaks. This represents two groups of electrons with different energies. The electrons in the first group, with low energy, affect local electron densities and the local plasma conductance. The electrons in the second group, with high energy, play the main part in the local excitation and the local ion production [17]. Also it is obvious that as the N_2 percentage in the gas mixture increases, area under *EEDF* curve increases and *EEDF* curve is shifted to low electron energy. This appears to support the increase in n_e with increasing the N_2 percentage in the gas mixture.

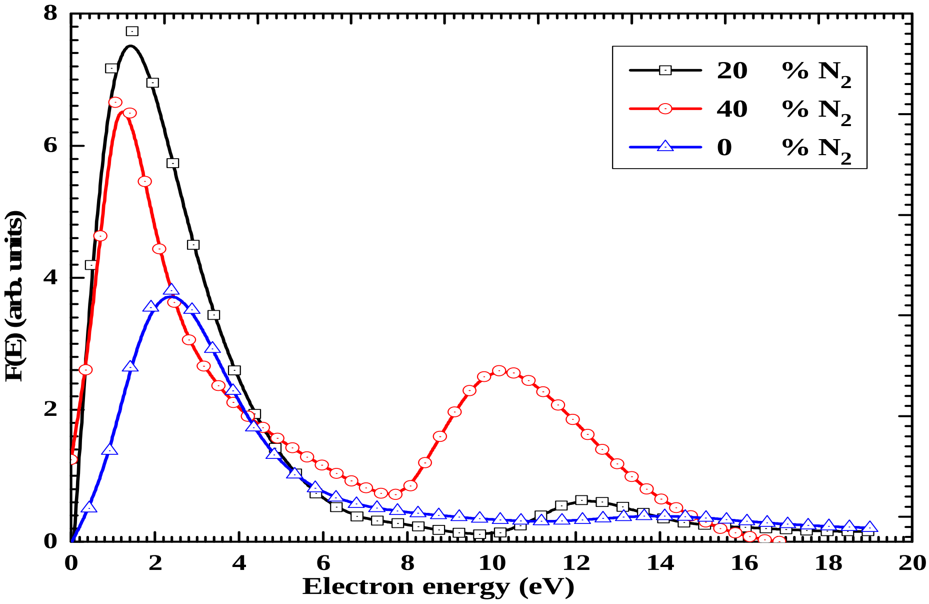

Fig. 8: The electron energy distribution function at different N_2 percentages, 0.2 torr filling pressure and 550 V DC discharge.

3.3) Plasma Electrical conductivity

Figure 9 shows the axial distribution of electrical conductivity. The effects of N_2 admixing show the same tendency as the electron number density since the electron electrical conductivity is directly depending on electron number density given by equation (5).

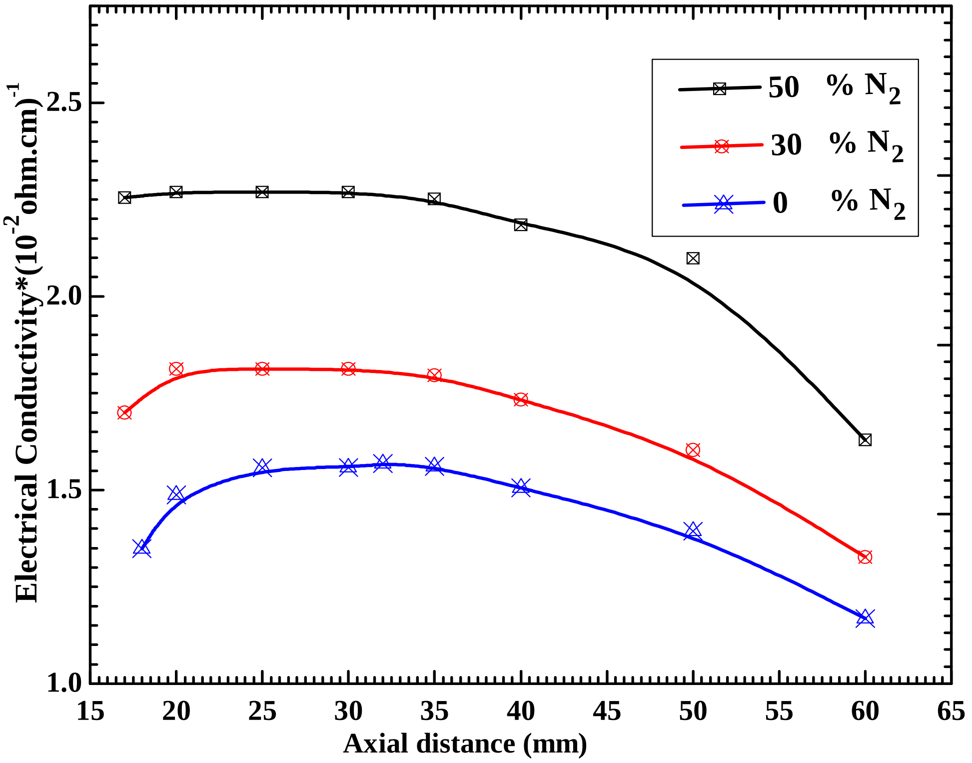

Fig. 9: Axial distribution of electrical conductivity for He plasma, at different N_2 percentages, 0.2 torr filling pressure and 550 V DC discharge.

CONCLUSION

The present study shows experimentally that electrical parameters, plasma properties and plasma electrical conductivity of DC He glow discharge can be influenced considerably by admixing of N_2 gas. The main results obtained here are summarized as follows:

(1) The addition of N_2 to He discharge causes an increase in the values of the discharge current at the same discharge voltage and gas pressure.
(2) The addition of N_2 to He discharge causes a decrease in the values of breakdown voltage and the cathode fall thickness of the discharge.
(3) The addition of N_2 to He discharge causes a decrease in the values of the electron temperature. Meanwhile electron and ion densities increase.
(4) The addition of N_2 to He discharge is indeed quite important in enhancing the electrical conductivity of the discharge.

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