V-I curves and plasma parameters in a high density DC glow discharge generated by a current-source

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Abstract. Nitrogen DC glow discharges, conducted in a cylindrical geometry, have been characterized using a new current-source able to provide 10⁻³ - 3 A for the sustainment of the discharge, instead of a conventional voltage-source. The V-I characteristic curves obtained from these discharges were found to fit the general form

\[ i(p) = A(p) k \nu^{1/4}, \]

whereby the plasma itself can be modeled as a voltage-controlled current-source. We conclude that the fitting parameters \( A \) and \( k \), which mainly depend on the gas pressure \( p \), are strongly related to the plasma characteristics, so much so that they can indicate the pressure interval in which the maximum plasma density is located, with values in the order of 10¹⁶ m⁻³ at reduced discharge potential (300–600 V) and low working pressure (10⁻¹ - 10¹ Pa).

1. Introduction
Electric discharges in gases carried out for several processes, such as those related with surface modification, demand plasma particle densities as high as possible as these are determinant to improve the treatment life time [1] and the general process efficiency [2].

High density plasma sources are usually RF, ECR or magnetron type. Yet DC is rarely the best choice due to their typical low density, in the order of 10¹⁵ m⁻³ [3] although DC discharges are still in use due to its easy operation, high homogeneity and low cost. They are operated by means a high voltage source at reduced values of the discharge current, limited by a series resistor [4].

By contrast, this work presents the study of a high density DC glow discharge conducted inside a cylindrical vacuum vessel and fed by a specifically designed high-voltage/high-current power source, by means of which we can gain control of the discharge current. This set up allows developing an electrical model that relates the three typical operational parameters of the discharge: current, voltage and gas pressure. The model is strongly related to the plasma density, so much that it predicts the pressure value at which the maximum density is attained, namely around 6.5×10¹⁶ m⁻³.

2. Experimental set-up
The figure 1 shows a graphical representation of the cylindrical vessel in which all tests were performed. The main components of the system are, as indicated: vessel, pressure sensor, gas inlet
port, outlet port to a 500 L min⁻¹ turbomolecular vacuum pump, high-voltage/high-current DC plasma source and access port for a Langmuir probe. The generated plasma volume is approximately 42 litres.

The DC power supply, shown as a schematic diagram in figure 2, is a current source converter (CSC) based on a parallel loaded series resonant circuit. The resonant loop (L and C) is polarized by means a full fridge MOSFET inverter switched at 45 kHz. A high voltage alternating current signal is obtained at the capacitor C and then rectified to DC and filtered out in order to provide a constant current power supply. The maximum power output of such a system is 1500 W and its output current (Iₑc) can be adjusted from 10⁻³ to 3 A by varying the input voltage (Vᵢ).

![Figure 1. General view of the discharge vessel and its main accessories.](image1)

![Figure 2. Schematic diagram of the DC high-voltage/high-current power supply.](image2)

Nitrogen glow discharges were carried out at pressure values between 10⁻¹ and 10¹ Pa, with a preliminary evacuation of the vessel down to a base pressure of 10⁻⁴ Pa. The voltage-current characteristic curves of the plasma were obtained by means of a high resolution digital voltmeter and a current meter. The plasma density was estimated through a 9 mm long, 0.36 mm in diameter, double cylindrical probe.

3. Results and discussion

The behaviour of the plasma current as a function of the applied potential was determined experimentally for different values of pressure. It is found an exponential relationship between those parameters leading to an electrical model of the plasma. Yeom et al [5] proposed a general form $i(\nu) \propto \nu^k$ where $k$ is a fitting exponent. This depends on the discharge type and its operational conditions of voltage ($\nu$) and current ($i$) [6]. Thus, we take this model to a more specific representation by means of an additional fitting coefficient as $i(\nu) = A(p)\nu^{k(p)}$, where $A(p)$ and $k(p)$ are the fitting functional parameters, specified for each pressure value ($p$).

The experimental $V$-$I$ curves, obtained from the nitrogen discharge are shown in figure 3 for some of the most significant pressure values, within a mean uncertainty of about ±15 V. The experimental data were processed and the fitting parameters $A(p)$ and $k(p)$ of the mode were obtained using exponential-logarithmic properties and the least square regression method. The resulting relationship, shown in figure 4, follows with good accuracy the experimental $V$-$I$ curves for each one of the pressure values.

Figure 5 displays the behaviour of the fitting parameters as a function of pressure. A maximum of $k(p)$ and a minimum of $A(p)$ are observed at a 4 Pa pressure. Meanwhile, the results from the plasma density measurements are presented in figure 6 with a $6.5\times10^{16}$ m⁻³ top density in coincidence with the above mentioned pressure of 4 Pa. Provided that the maximum densities are found close to this value, the proposed electrical model proves to simulate satisfactorily the behaviour of the electrical
operational conditions of the discharge as well as predicting the pressure interval where the maximum plasma density is located.

The location of the 4 Pa value is also coincident with the pressure of minimum breakdown voltage needed to ignite the discharge, according to the Paschen law [4] namely, the pressure at which the ionization process is easier. Note that the maximum density is achieved at relatively low pressure (4 Pa), reduced discharge potential (between 300 and 600 V, in accordance to figure 3) and high plasma current (up to 3000 mA, in figure 6).

Figure 3. Experimental V-I curves for some pressure values.

Figure 4. Fitting of the V-I curves through the model \( i(\nu) = A(p)\nu^{k(p)} \).

Figure 5. Relationship between the fitting parameters, \( A(p) \) and \( k(p) \), and gas pressure

Figure 6. Electron plasma density as a function of gas pressure

A direct dependence of the plasma electron density on the current discharge, observed in figure 6, is due to the substantial increment of the current density (defined as current by unit of area [7]). The latter is clearly related to the plasma density as \( j = en_e\mu E \) where \( j \) is the current density, \( e \) electron charge, \( n_e \) electron plasma density, \( \mu_e \) is the electron mobility and \( E \) is the electric field [4].

Our CSC provides the electric field required for the discharge sustainment with a constant current density in the vicinity of the cathode, allowing an electron flow toward the plasma which is proportional to the applied current. Thus, the ionized particle population can be increased as the applied current grows up. The small variations in the electron density for each value of the discharge current can be attributed to differences in electric field intensity at different values of the current as well as to the differences in mobility at different values of the gas pressure.
It is confirmed an outstanding increment between 10 and 100 times in density, with respect to our previous work. Discharges performed by López-Callejas et al [8] in the same vessel geometry but with the convectional voltage-source at low plasma current provide maximum densities of about \(10^{14} \text{ to } 10^{15} \text{ m}^{-3}\) achieved at pressures between 2.6 and 40 Pa.

In comparison with the performance of other plasma sources, the plasma density achieved here is comparable to those of more complex plasma sources such as RF, ECR and magnetron systems. For instance, Takechi et al [9] have used an RF plasma source in order to generate a plasma volume of about 32 litters with densities up to \(3\times10^{16} \text{ m}^{-3}\), Pu et al [10] report \(8\times10^{16} \text{ m}^{-3}\) densities in Nitrogen at 0.7 Pa by means of an ICP plasma source as well as \(14\times10^{16} \text{ m}^{-3}\) at 0.7 Pa in an ECR generated discharge. Li et al [1] achieved densities from \(2\times10^{15}\) to \(2.4\times10^{16} \text{ m}^{-3}\) in an Argon discharge filling a plasma volume of about 4.2 litters thanks to a high voltage pulsed source. Pessoa et al [11] have accomplished discharges at 0.7 Pa of nitrogen-argon mixtures in a 6 litter cylindrical vessel by means of a hollow cathode magnetron plasma source reporting \(1\text{ - } 7\times10^{16} \text{ m}^{-3}\) densities. The plasma density obtained with our CSC reaches similar values to those of all the mentioned examples. Furthermore, our discharge is developed in a larger plasma volume and with a far less expensive plasma source which is also more easily operated and maintained.

4. Conclusions

We have presented a study of the experimental results obtained from a high density DC plasma source in the glow regime produced by a special current source converter with a high-voltage/high-current output, capable to provide up to 1500 W to the discharge.

An electrical model of the plasma, in the general form \(i(\nu) = A(p)\nu^{k(p)}\), has been developed for the system. The model is capable of reproducing with sufficient accuracy the experimental behaviour of both voltage and current as a function of the gas pressure in a nitrogen glow discharge. The plasma characterization confirms that the fitting parameters \(A(p)\) and \(k(p)\) are functions of the gas pressure, while their graphic evolution reveals the pressure interval where the maximum plasma density is reached. The experimental results suggest that the plasma density has been improved from 10 to 100 times with respect to our previous work, which makes it comparable to those obtained from high density plasma sources, provided that density values as high as \(6.5\times10^{16} \text{ m}^{-3}\) have been attained.

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