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OXYGEN REFLEX PLASMA DIAGNOSTICS

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An oxygen reflex discharge was investigated. The voltage-current characteristics of the discharge have been measured at pressures between 6.65×10^{-2} Pa and 13.3 Pa (5×10^{-4} to 10^{-1} torr). Other discharge parameters, i.e. electron temperature and plasma concentration, were determined for three different discharge currents using Langmuir electrostatic-probe technique. A sheath theoretical model gave us another set of results for plasma concentration which confirmed the results obtained by the probe technique. Concentrations obtained (about 10^{17} m^{-3}) are very high, comparable to those in RF reactors, so the reflex plasma can be used for technological purposes.

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1. *Introduction*

The reflex discharge or Penning discharge (PIG) has been of interest from the early decades of this century [1-3] up to the recent years [4]. Recently, reflex discharges have found increased application in the design of plasma reactors suitable for environmental friendly plasma technologies for surface modification [5].

In a Penning discharge plasma, an electron oscillates back and forth between two cold cathodes and spends a long time before being removed from the discharge. This leads to a high ionization degree. Therefore, the Penning resembles of a capacitively coupled, radio-frequency discharge plasma of the double-diode type [4,6]. However, the Penning plasma reactor is based on a direct current plasma where the discharge techniques and power supplies are simpler, rather on a radio-frequency plasma as used up to now.

A more quantitative understanding of this type of discharge than the currently available would facilitate future designs of such plasma reactors. It is the aim of this work to determine the parameters of such a reflex discharge in a previously reported design of a reactor [5].

In this work, we present results of the study on an oxygen reflex plasma. The oxygen gas pressure was varied from 6.65×10^{-2} Pa and 13.3 Pa (5×10^{-4} to 10^{-1} torr) and the discharge current was varied from 10 mA to 200 mA. The schematic of reflex plasma and voltage-current characteristics are presented in Sect. 2. For plasma diagnostic we used Langmuir probe measurements. In Sect. 3, we describe theoretical relations used for experimental data processing and in Sect. 4, the parameters calculated by two different methods are analyzed.

2. *Experimental set-up*

Schematic of the discharge chamber used for producing the reflex plasma and electrical schematic are presented in Fig 1. The cathodes have a diameter of 80 mm and they are placed face-to-face with a 20 mm gap between them. The ring-form anode is placed symmetrically with respect to the cathodes. The magnetic field, generated by two permanent magnets placed on the back of the cathodes, has an intensity of almost 5×10^{-3} T. A 3 mm diameter plane probe is placed in the geometric centre of the reflex discharge.

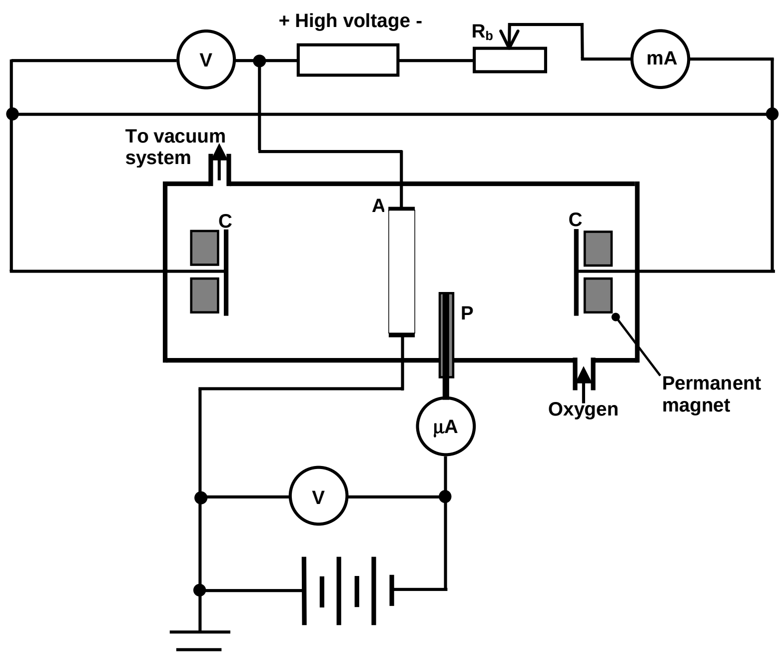

Fig 1. Experimental set-up.

High voltage was supplied by a STATRON TYP 4205 generator. Vacuum system consisted of a rotary vacuum pump with a pumping speed of 18 m^3/h and a Roots pump with a pumping speed of 150 m^3/h. The vacuum system provides a base pressure as low as 6.65×10^{-3} Pa (5×10^{-5} torr).

The flow-rate of oxygen through the discharge chamber was controlled by a pressure regulator and a needle valve, and it was measured with a flow-rate meter. Pressure in the discharge chamber was monitored with the Pirani and Penning gauges.

Typical voltage-current characteristics are presented in Fig. 2 for seven pressures between 6.65×10^{-2} Pa and 13.3 Pa (5×10^{-4} to 10^{-1} torr). One can notice that for high pressures, small variations of the discharge voltage produce large variations of the discharge current.

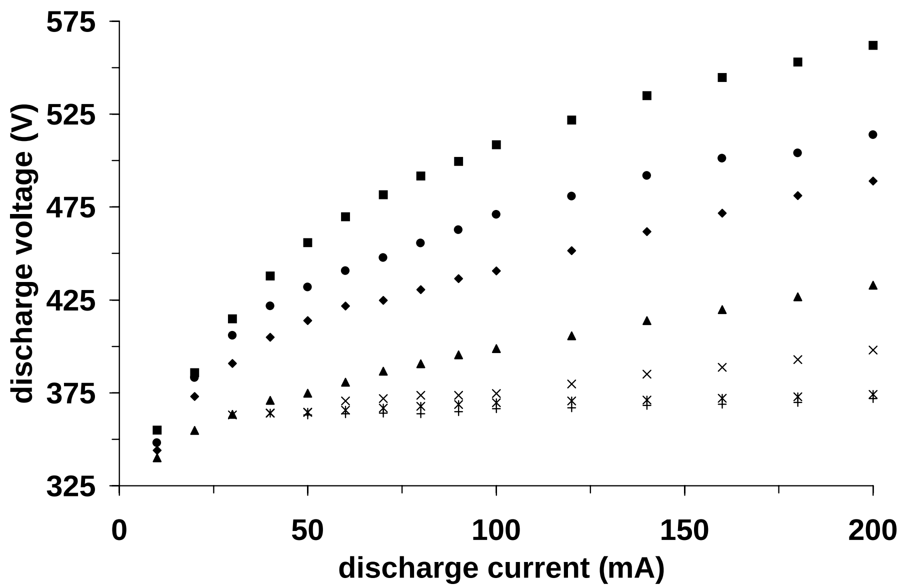

Fig 2. Voltage - current characteristics for seven oxygen gas pressures.

High discharge currents are due to higher degrees of ionization and, consequently, higher efficiencies of different processes in plasma. The aim is to realize a compromise between such high ionization degrees and instabilities of the discharge at higher pressures. Our tests show that the best condition is to run such a reactor at the pressure of 1.33 Pa (10^{-2} torr).

3. Theory

Langmuir probes are indispensable diagnostic tools for the investigation of plasma parameters such as electron density, N_e, ion density, N_+, and electron temperature, T_e [7–10]. The most widely used method for the determination of electron temperatures and densities is the application of plots of $\ln I_e$ vs. V_p from electron retarding region (I_e is the net electron current collected by the probe and V_p is the probe potential relative to the plasma potential). Such a plot is linear for the case of a Maxwellian electron energy distribution with the slope $S = e/(kT_e)$, where e is the electron charge and k the Boltzmann constant. From this, one obtains T_e as

$$T_e = \frac{e}{k} \frac{\Delta \ln I_e}{\Delta V_p}. \tag{1}$$

To obtain the positive ion density N_+ (which is equal to the electron density N_e plus the negative ion density N_-) from the ion saturation region, we used the formula

$$N_+ = \frac{I_{+,\mathrm{sta}}}{eA_p} \sqrt{\frac{M_+}{kT_e}}, \tag{2}$$

where $I_{+,\mathrm{sat}}$ is the positive-ion saturation current to the probe, A_p is the probe area and M_+ is the mass of positive ions.

We applied another method to obtain the positive ion density N_+ in which one uses a plasma model based on the particle transport at the boundary plasma – cathode fall sheath.

This model starts with the assumption that the positive ions, in motion from the plasma toward the cathodes, pass through the cathode fall region where the voltage is almost equal to the discharge voltage V_d. For the description of motion of positive ions in the cathode fall region, we consider a mobility-limited ion drift motion. In this case, the average ion energy at the cathode surface is proportional to $\sqrt{V/(pd)}$, where d is the cathode fall distance which, in that case, can be measured experimentally.

Taking into consideration the arguments of the above discussion, the ion velocity v_+ in the cathode fall region is given by the expression

$$v_+ = K\sqrt{\frac{\mathrm{d}V}{\mathrm{d}x}}, \tag{3}$$

where K is a mobility-like factor which is inversely proportional to the square root of the gas pressure [11].

From the charge conservation and the assumption of no ionization and recombination in the cathode fall region, it appears that the ion flux density J_+, anywhere along the positive distance x (at the boundary between the plasma and the sheath) is constant, i.e.,

$$J_+ = eN_+v_+ . \tag{4}$$

In the cathode fall region, the electric field is given by the Poisson equation

$$\frac{\mathrm{d}V}{\mathrm{d}x} = -\frac{eN_+}{\epsilon_0}, \tag{5}$$

where ϵ_0 is the permitivity of vacuum. By eliminating the ion density in the Poisson equation using Eq. (4) and replacing v_+ from Eq. (3), a differential equation in V and x is obtained that can be solved by direct integration. With the boundary conditions $\mathrm{d}V/\mathrm{d}x$ and $V = 0$ at $x = 0$, and some rearrangements, the result is

$$J_+ \simeq 1.43 \, \frac{\epsilon_0 \, K \, V^{3/2}}{x^{5/2}} \,, \tag{6}$$

and

$$\frac{V_x}{V} = \left(\frac{x}{d}\right)^{5/3} . \tag{7}$$

On the other hand, the ion current density injected from the plasma into the cathode fall region follows from the Bohm criterion, and it is usually expressed as

$$J_+ = e \, N_+ \sqrt{\frac{kT_\mathrm{e}}{M_+}} \, . \tag{8}$$

By combining Eqs. (3), (6), (7) and (8), one obtains

$$N_+ \sqrt{T_\mathrm{e}} = 1.43 \sqrt{\frac{M_+}{k}} \, \frac{\epsilon_0 \, K \, V^{3/2}}{e \, d^{5/2}} \, . \tag{9}$$

The cathode fall length, cathode fall voltage and electron temperature that appear in Eq. (9) are determined experimentally. The value of the constant K for oxygen is taken from the literature for one value of the pressure; any other value one can subsequently calculate.

4. *Results and discussion*

We used a 3 mm diameter wolfram plane electrostatic Langmuir probe which was placed at the centre of the plasma. For a discharge at 1.33 Pa oxygen pressure, the measurements of the probe voltage-current characteristics were done at discharge currents of 60 mA, 80 mA and 100 mA. The voltage-current characteristics were obtained by varying the probe voltage from –200 V to 0 V with respect to the grounded anode. A typical plane probe characteristic is presented in Fig. 3. For these relatively small discharge currents, only one group of electrons was identified; the experiments done at some larger currents (about 200 mA) show that there are actually two groups of electrons [5].

At the 1.33 Pa oxygen pressure and the discharge current range from 20 mA to 100 mA, the values obtained for the cathode fall voltage V (assumed to be equal to discharge voltage) and the cathode fall length d are given in Table 1. For an oxygen pressure of 1.33 Pa, the value of the constant K is $K = 137.56 \, \mathrm{m^{-3} V^{-1/2} s^{-1}}$. Using these data in Eq. (9), the results obtained for the product $N_+ \sqrt{T_\mathrm{e}}$ are presented in Fig. 4 as a function of the discharge current.

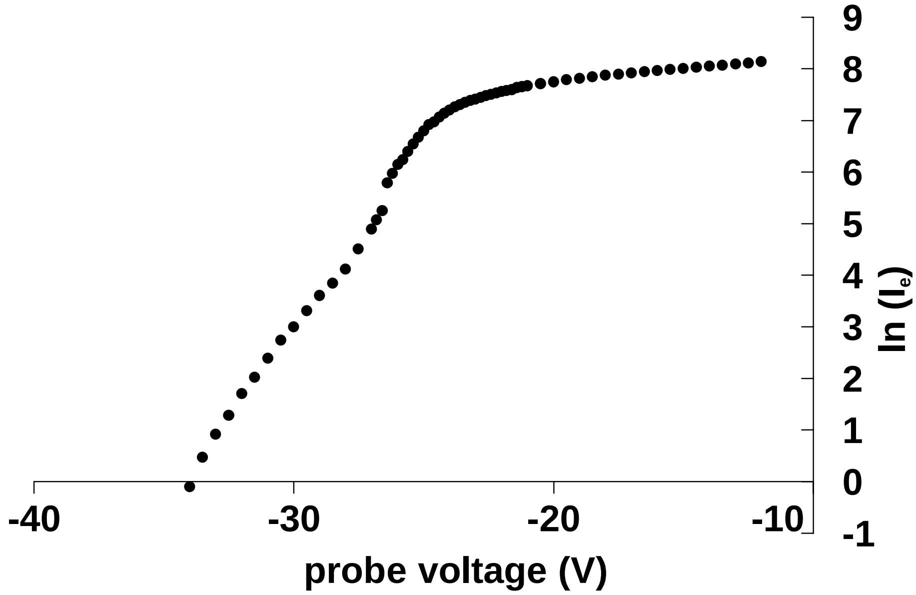

Fig 3. Probe voltage - current characteristic for 100 mA *discharge current and 1.33* Pa *oxygen gas pressure.*

TABLE 1. Variation of the cathode fall voltage, cathode dark space length, d, and $N_+\sqrt{T_e}$ *vs. discharge current.*

I (mA)	20	30	40	50	60	80	100
V (volts)	354	367	376	384	386	399	409
d (mm)	5.50	5.00	4.50	4.25	4.00	3.50	3.00
$N_+\sqrt{T_e}$ (10^{18} m^{-3} $K^{1/2}$)	2.84	3.81	5.14	6.11	7.17	10.52	16.05

The values of the electron temperature and positive-ion density are given in Table 2. The values N_{+2} have been obtained using Eq. (2), and the values N_{+9} have been obtained using Eq. (9).

Due to its intense chemical activity, oxygen reacts with the wolfram at the surface of the probe, so the probe needs to be periodically cleaned. Tests showed that only small changes of the probe current occur in time intervals of about 20 minutes. These tests were conducted because any major modification in the probe current may lead to wrong experimental results. By using the techniques that

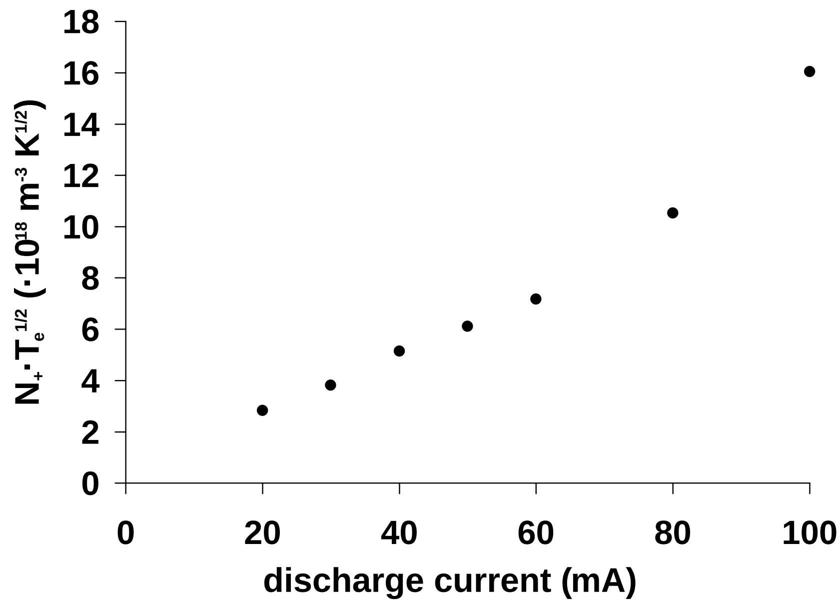

Fig 4. $N_+ \sqrt{T_e}$ *vs. discharge current.*

TABLE 2. Cathode fall voltage and length, electron temperature and plasma density for three discharge currents.

I (mA)	V (V)	d (mm)	T_e (K)	N_{+2} (m^{-3})	N_{+9} (m^{-3})
60	386	4.00	35900	0.47×10^{17}	0.37×10^{17}
80	399	3.50	26700	0.97×10^{17}	0.64×10^{17}
100	409	3.00	15900	1.15×10^{17}	1.27×10^{17}

were presented in a previous work [12], we observe also that there are no waves or instabilities in the plasma.

5. *Conclusion*

We investigated an oxygen reflex plasma suitable for plasma processing with applications in ashing of photoresist, oxidation or deposition of thin film oxides. We presented voltage-current characteristics of the discharge in the pressure range of 6.65×10^{-2} Pa and 13.3 Pa (5×10^{-4} to 10^{-1} torr). We measured the electron temperature at three discharge currents by using the Langmuir probe technique.

For these relatively small discharge currents, electron temperatures were found to be in the range of 11000 to 35000 K and they are decreasing as the discharge currents rise. At the same time, we have calculated the ion density first by using the electron retarding region of probe characteristic and subsequently by using a plasma model based on the particle transport at the boundary plasma – cathode fall sheath. The two results are in good agreement with each other.

The determined values of the plasma concentration (about 10^{17} m^{-3}) are large enough so this plasma can be used for technological purposes. The internal parameters of this discharge seem to be easily tunable – meaning that technological applications could be highly efficient.

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DIJAGNOSTIKA KISIKOVE REFLEKSNE PLAZME

Istraživali smo kisikovu refleksnu plazma. Mjerili smo ovisnost napon–struja na tlakovima između 6.65×10^{-2} Pa i 13.3 Pa (5×10^{-4} do 10^{-1} torr). Odredili smo druge parametre izboja, elektronsku temperaturu i gustoću, za tri jakosti struje, primjenom Langmuirove elektrostatske sonde. Pomoću slojnog teorijskog modela dobili smo drugi skup ishoda mjerenja koji je potvrdio ishode postignute pomoću sonde. Postignute gustoće iona (oko 10^{17} m^{-3}), koje su usporedive s onima u radiofrekventnim reaktorima, toliko su velike da se refleksna plazma može primijeniti u tehnološkim postupcima.