Spatially resolved characterisation of plasma parameters in a double inductively coupled plasma: experiment and simulation

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Abstract: A double inductively coupled plasma is studied experimentally and compared to hybrid plasma simulations. A multipole resonance probe is used for radial resolution of electron densities and electron temperatures. Tuneable diode laser absorption spectroscopy measures argon metastable state densities and gas temperatures. Hybrid simulations performed using the Hybrid Plasma Equipment Model (HPEM) are compared to the obtained experimental data.

Keywords: multipole resonance probe, atomic oxygen, argon metastables, 2-D simulation

1. Introduction

Plasma processes are employed in many different applications, ranging from semiconductor and microelectronic manufacturing to surface disinfection. In order to achieve process control in such applications, a detailed understanding of the plasma processes involved is needed. Furthermore, large scale applications require the consideration of process homogeneity hence spatially resolved characterisation of such processes becomes increasingly important.

Insight into the plasma can be gained by experimental diagnostics as well as by computational models. In industrial processes, the application of experimental diagnostics often is difficult due to lack of equipment, accessibility or possible disturbance of running fabrication processes. In these cases, well-developed computational models can help provide the necessary insight into the plasma without the need for extensive experiments. However, in order to gain accurate results from a computational model, it needs to be validated against experimental data.

In this contribution, a double inductively coupled plasma, (DICP) specifically designed for biomedical applications, is studied with respect to its fundamental plasma parameters. A focus is placed on the radial resolution of electron densities and temperatures allowing a direct comparison to 2-D plasma simulations. In addition, the gas phase chemistry is analysed with regards to oxygen-containing gas mixtures due to their ability to produce large fluxes of reactive species such as atomic oxygen and UV photons, which play a major role in biomedical and surface processing applications [1,2].

2. Experimental setup

The experiments are conducted in a double inductively coupled plasma system depicted in figure 1. It features a cylindrical stainless-steel chamber with several flanges attached at half-height, allowing for the application of several experimental diagnostics to characterise subsequent plasma processes. The chamber has a diameter of 400 mm and a height of 200 mm. Top and bottom of the chamber consist of 20 mm thick quartz plates on which the ICP coils are mounted. A detailed description of the setup is given elsewhere [3]. The measurements include a variation of power, pressure and argon/oxygen concentration in the gas mixture. The parameters are chosen in accordance with those in [4] to allow for validation.

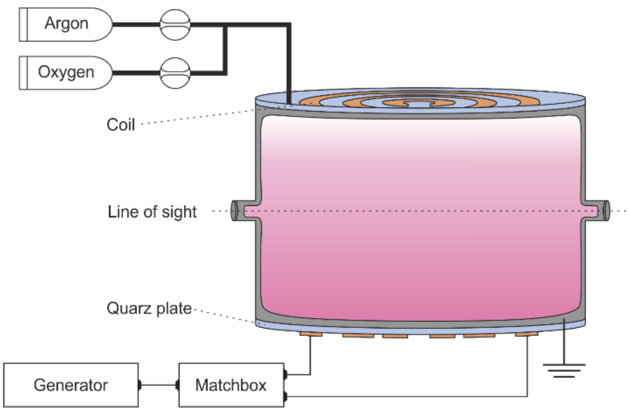

Fig. 1. Schematic of the used double inductively coupled plasma system.

The electron density and electron temperature are measured along the diameter of the chamber using the multipole resonance probe (MRP) [5]. Tuneable diode laser absorption spectroscopy is used to measure the absorption profile of the transition Ar ($1s_5 \rightarrow 2p_6$) at 772.376 nm [6], yielding the line integrated neutral gas temperature and argon metastable state densities. Absolutely calibrated optical emission spectroscopy is applied for determination of absolute intensities of atomic oxygen emission lines. The transitions investigated are $O(^5P)$ - $O(^5S)$ and $O(^3P)$ - $O(^3S)$ at 777.1 nm – 777.6 nm and 844.6 nm – 844.7 nm respectively. These are investigated for future validation of collisional radiative modelling of the discharge.

3. Hybrid plasma simulations

The double inductively coupled plasma system is additionally investigated computationally by using the Hybrid Plasma Equipment Model (HPEM) developed by Kushner and co-workers [7]. The simulation yields spatially resolved information on parameters such as the argon metastable density, of which experiments can only provide line of sight integrated values. Thereby the simulation not only validates the experimental data, but also helps to extend the parameters obtained for characterisation.

HPEM handles a variety of different geometries, analyses different gas chemistries and generates the corresponding plasma parameters. In this work, the DICP is modelled using the electromagnetics module, the electron energy transport module, the fluid kinetics-poisson module and the plasma chemistry Monte Carlo module.

4. Preliminary results

All plasma processes use an argon-oxygen gas mixture as process gas. The oxygen content in the gas mixture is varied from 0 % to 20 % while keeping the total gas flow constant at 100 sccm. The discharge power is varied from 200 W to 800 W and the process pressure from 2 Pa to 20 Pa.

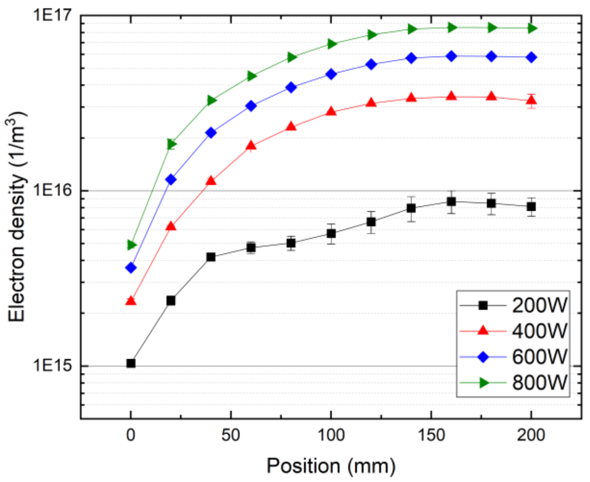

Fig. 2. Spatially resolved electron density measured at a pressure of 5 Pa and oxygen content of 20 % for different discharge powers. A position of 0 mm corresponds to the reactor wall, 200 mm to the centre of the discharge.

The electron density is measured spatially resolved along the radial axis of the reactor. Figure 2 shows the electron density in spatial resolution for different discharge powers. The electron density reaches its maximum in the centre of the discharge with values up to $8.5 \times 10^{16}\,m^{-3}$ and drops down to $1.0 \times 10^{15}\,m^{-3}$ at the walls. Increasing the discharge powers leads to an overall increase in the measured electron density. The shape of measured electron density profiles is similar for power levels from 400 W to 800 W. For the minimum power of 200 W, the shape exhibits a dip from 50 mm to 150 mm.

First results of the simulation show similar trends for the spatially resolved electron density. Simulated values slightly exceed measured values for the same powers. It is assumed this is due to the designated generator power leaving the matching system not being equal to the absorbed power in the plasma system. These possible losses are not accounted for in the simulation.

Optical emission spectroscopy measures the line of sight integrated absolute intensity of different oxygen transitions. Figure 3 displays the absolute intensity of the $O(^5P)$ - $O(^5S)$ transition for varying discharge powers and Ar-O_2 gas mixtures. Increasing the discharge power leads to higher oxygen emission. Increasing the oxygen content in the gas mixture yields higher emission for admixtures up to 5 %. For higher admixtures, the oxygen emission drops.

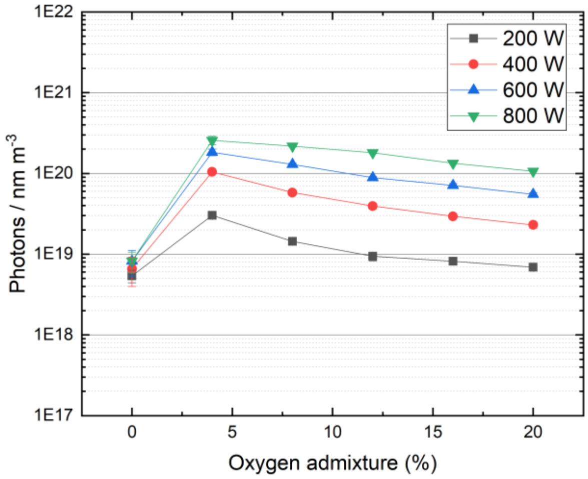

Fig. 3. Line of sight integrated absolute intensity of the $O(^5P)$ – $O(^5S)$ transition at a pressure of 5 Pa for various discharge powers and Ar-O_2 mixtures.

5. Conclusion

In this contribution, a double inductively coupled plasma system was characterised with regards to spatial resolution of electron density and electron temperature and line of sight integrated information on gas temperature, argon metastable state densities and oxygen emission. Various process parameters were varied. Simulations using the Hybrid Plasma Equipment Model, were compared to the experimental results and to gain insight into the spatial resolution of additional parameters. First experimental measurements showed trends corresponding well to earlier results. Preliminary results of the simulation yielded electron densities slightly above measured values but were overall in good agreement with the experimental data.

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