Journal of Optoelectronics and Advanced Materials Vol. 7, No. 5, October 2005, p. 2471 - 2475

CHARACTERIZATION OF A SURFACE-WAVE SUSTAINED PLASMA DISCHARGE IN A CO-AXIAL STRUCTURE

S. Letout[a,b*], L. L. Alves[b], C. Boisse-Laporte[a], P. Leprince[a]

[a]Laboratoire de Physique des Gaz et Plasmas, Université Paris-Sud, 91405 Orsay Cedex, France
[b]Centro de Física dos Plasmas, Instituto Superior Técnico, 1049-001 Lisboa, Portugal

The present work introduces the preliminary experimental characterization of a low-pressure microwave discharge in a coaxial structure. The discharge radial description is simulated using a 1D-moment method code, which couples particle and energy transport to the field distribution and Poisson's equations. Cylindrical Langmuir probe and emission spectroscopy measurements are used to give a spatial description of the high-density plasma. The effects on probe characteristics of the high-intensity resonance field are mentionned. Radial profiles are compared to numerical simulations.

(Received April 1, 2005; accepted September 22, 2005)

Keywords: Plasma, Microwave, Surface Wave, Electron-Plasma Resonance, Langmuir Probe, Emission Spectroscopy, Self-Consistent Moment Method Simulation.

1. Introduction

The coaxial structure under analysis here was initially developed as an additional ionisation device for an Ionised Physical Vapour Deposition (IPVD) system [1]. It was then decided to carry out a fundamental study on the electron population of low-pressure argon discharges produced in this device, as results may be extrapolated to similar high-density microwave discharges produced in large-scale planar reactors for material processing [2,3].

A definite advantage of this azimuthally symmetric structure was evidenced by the self-consistent description obtained in [4,5], which reported the development of an electron-plasma resonance in the vicinity of sheath regions. These resonances occur wherever $\omega_p \sim \omega$ (ω is the microwave excitation frequency; $\omega_p = (n_e e^2/\varepsilon_0 m_e)^{1/2}$ is the electron-plasma frequency ; e and m_e are the electron charge and mass, respectively ; n_e is the electron density ; and ε_0 is the vacuum permittivity), for example as result of the strong radial gradient of n_e in near sheath regions. This coaxial device constitutes an interesting alternative to large planar configurations [6,7,8,9] in studying the generation of expected hot-electron fluxes.

The following reports a preliminary experimental characterization of a low-pressure, surface-wave sustained argon discharge, produced in this coaxial structure. The aim is to further investigate the wave-plasma power coupling and the energy deposition processes in the plasma. The radial profiles of the electron density $n_e(r)$ and temperature $T_e(r)$ were measured under different conditions, using a cylindrical Langmuir probe. Results yielded typical electron densities of 10^{11} to 10^{12} cm^{-3} and temperatures around 2 eV, for pressures ranging from 10 to 100 mTorr. The measured profiles were compared to simulation results obtained with a self-consistent 1D-moment method numerical code. Spatially resolved emission spectroscopy was used to monitor the axial intensity of the plasma radiation.

2. Presentation

The experimental set-up presented in Fig. 1 was designed in order to allow Langmuir probe measurements along the discharge radius (r) for different axial positions (z), and emission spectroscopy measurements along the discharge axis.

* Corresponding author: simon.letout@pgp.u-psud.fr, simon.letout@ist.utl.pt

A 2.45 GHz magnetron is connected to the rectangular wave guide. A coupling device develops the incoming rectangular mode into a coaxial one, using a copper tube (r_c=5mm). A quartz tube (r_q=15mm) delimits vacuum inside a metallic cylindrical chamber (r_m=80mm), allowing a plasma to be created outside the quartz tube. A cut-off electron density of $n_c = 0.745 \times 10^{11}$ cm^{-3} needs to be reached for a plasma mode to propagate. It is assumed that only the fundamental mode TM_{00} propagates and sustains the plasma.

The present study focused on argon low-pressure (10-100 mTorr) discharges, for injected microwave powers up to 1 kW. Measurements of the electron density and temperature profiles were performed using a 3mm - 50μm cylindrical probe. The collection (Tungsten) part of the probe was bent horizontally to obtain a ~1mm radial resolution. Emission spectroscopy measurements were also made, collecting light from a neutral argon line (3948.9 Å) through an optical fibre connected to a spectrometer.

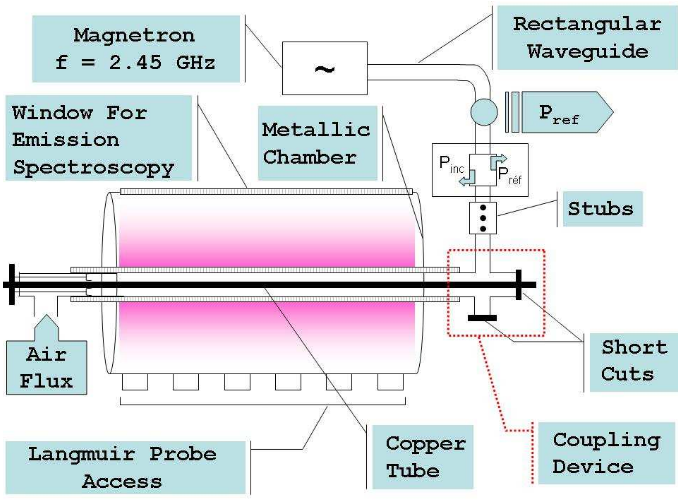

Fig. 1. Longitudinal cut of the experimental set up.

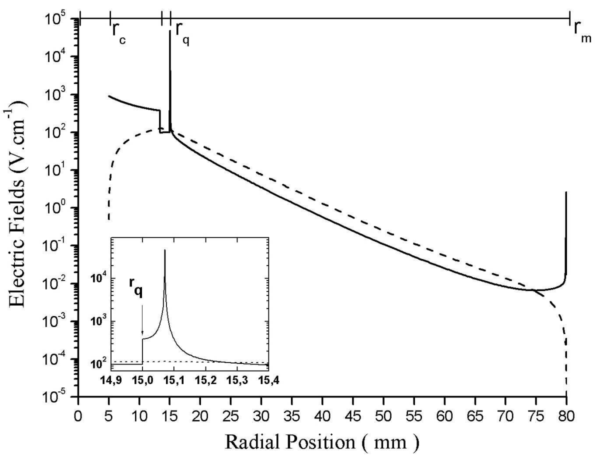

Fig. 2. Calculated radial distribution of the wave electric field components, at 30 mTorr pressure and 5.7×10^{11} cm^{-3} radially averaged electron density. E_r: solid line, E_z: dashed line. The lower left graph is a blow-up of the inner resonance region.

The radial profiles of the electromagnetic fields and the electron density and energy were obtained from a self-consistent 1D model. The corresponding numerical code couples charged particle and energy transport equations to Maxwell's equations for the TM_{00} mode (taking into account the electron-plasma resonance) and to Poisson's equation for the electrostatic space-charge field. The calculated radial distribution of the electromagnetic field components is shown in Figure 2, where one can observe the resonance peaks of the radial electric field, located in the vicinity of space-charge sheaths (near the quartz tube and near the outer metallic cylinder).

3. Results and discussion

Electron density and temperature values were obtained from probe measurements using Langmuir's theory. As shown in Fig. 3, the electron density profiles are generally well predicted by simulations. Experimental electron temperatures range between 1.5 and 2 eV, depending on the gas pressure. We have also achieved a good qualitative agreement between measurements and calculations of the electron temperature radial profile (see Fig. 4). To justify the fact that calculations overestimate measured electron temperature values, one has to consider that a more precise coupling of the resonance peaks with the electron population is expecting to lead to changes in the energy balance description and also that the model yet only takes into account electron collisions with ground state atoms.

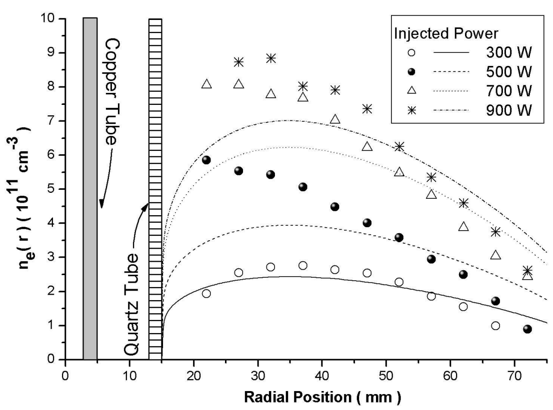

Fig. 3. Measured (points) and calculated (lines) electron density radial profiles at 30 mTorr pressure, and for different microwave powers (300, 500, 700, 900 W).

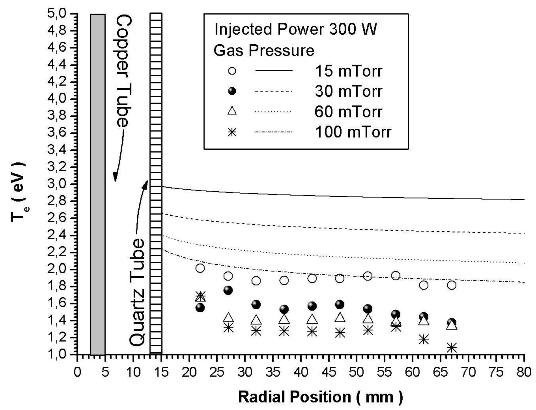

Fig.4. Measured (points) and calculated (lines) electron temperature radial profiles at 300 W microwave power, and for different pressures (15, 30, 60, 100 mTorr).

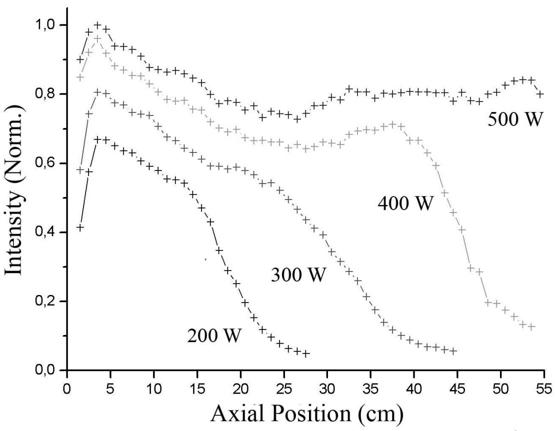

Fig. 5. Experimental axial variation of the 3948.9 Å argon line at 30 mTorr pressure, and for different microwave powers (200, 300, 400, 500 W).

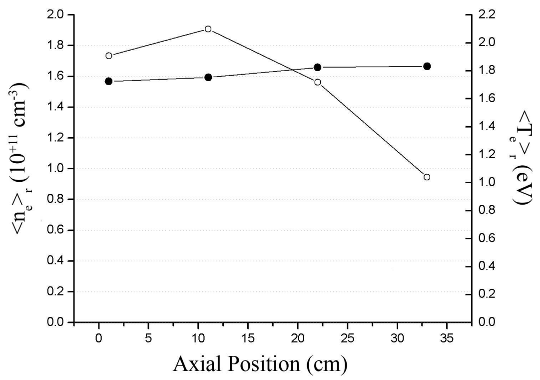

Fig. 6. Experimental axial variation of the radially averaged electron density $<n_e(r)>$ (empty dots) and temperature $<T_e(r)>$ (full dots), at 30 mTorr pressure and 300 W microwave power.

Fig. 5 shows axial line intensity profiles, obtained under different working conditions. At low injected powers, we observe a rapid decrease in the radiation intensity, implying that all the injected wave-power is transferred to the plasma before reaching the ending shortcut. At higher injected powers, the latter decrease is not observed and the signal is roughly modulated. This may indicate that a stationary wave configuration is established, leading to axial modulations of the microwave power, hence of the electron density.

Fig. 6 shows the axial variation of the radially averaged electron density $<n_e(r)>$ and temperature $<T_e(r)>$ profiles, obtained from probe measurements. Notice that while $<T_e(r)>$ is almost constant along z, the values of <$n_e(r)$> measured at z = 11 and 33 cm are different by a factor 2, which agrees with the corresponding 300 W axial profile of radiation emission (see Fig 5).

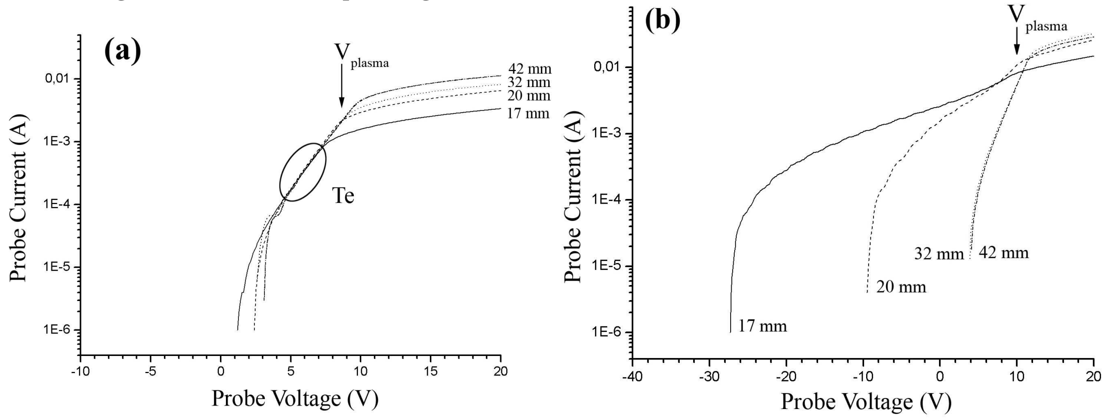

Fig. 7. Probe characteristics obtained at 30 mTorr pressure, for different radial positions (17, 20, 32, 42 mm from the quartz tube), and the following microwave powers : (a) 300 W, (b) 700 W.

Fig. 7 presents measured probe characteristics, obtained at different radial positions, for 30 mTorr gas pressure and two different microwave powers. In this figure, we have marked the approximated positions of the plasma potential (V_{plasma}), corresponding to the change in the slope of the probe characteristic at high V_{probe}. At low injected power, the slope of the logarithmic probe characteristics indicates the existence of a constant electron temperature over the radius [see the circle in Figure 7 (a)]. At higher power [see Figure 7 (b)], characteristics measured far away from the quartz tube still show a constant electron temperature, while a strong deformation of the characteristics is observed for $V_{probe}<V_{plasma}$, when the probe is moved closer to the quartz tube (usually < 20 mm). Such deformations are probably associated to the existence of a high-energy electron population, generated during the transit time within the narrow resonance region located near the quartz tube. But it is also possible that the high-intensity excitation field, at least partially, modifies the electric field of the probe, thus affecting current collection.

4. Conclusions

In this work, encouraging comparisons between measurements and simulations were achieved for the radial profiles of the electron density and temperature, with a low-pressure microwave discharge produced by a coaxial structure.

The experimental probe diagnostics are to be pursuit considering the possible effects on the electron population. The use of a planar probe could provide valuable information about the directionality of the high-energy electron flux, the isotropy of the electron distribution and the possible perturbation of the excitation field. The analysis of probe characteristics obtained at different gas pressures could be related to the variation of the resonance intensity.

Results also show that the description of the plasma needs to be improved. First, a more accurate formulation of the electron and energy transport equations could induce significant changes in the description of resonance regions. Energy transport through the diffusion of metastable species toward the walls and stepwise electron-neutral ionisation collisions are also expected to play a significant role, which can be accounted for by coupling a collisional-radiative model to the present 1D-moment method code.

The symmetry features with the present coaxial device allow its description by a one dimensional model, in contrast with large area planar reactors that demand a more thorough geometric analysis. Moreover, this model provides an interplay between simulation and experiment, which creates the opportunity to study the phenomenon of non-collisional electron heating by the field resonances, and its effects on the discharge energy budget.

References

[1] C. Boisse-Laporte, O. Leroy, L. de Poucques, B. Agius, J. Bretagne, M. C. Hugon, L. Teulé-Gay, M. Touzeau, Surface and Coatings Technology **179**, 176 (2004).
[2] M. Nagatsu, G. Xu, M. Yamage1, M. Kanoh, H. Sugai, Jpn. J. Appl. Phys. **35**, L341 (1996).
[3] I. P. Ganachev, H. Sugai, Plasma Sources Sci. Technol. **11**, A178 (2002).
[4] L. L. Alves, G. Gousset, Proceed. MD5 (A.Ohl ed.), INP Greifswald, Germany, p.90, 2003.
[5] L. L. Alves, G. Gousset, S. Vallée, IEEE Trans. on Plasma Sci. **31**, 572 (2003).
[6] J. Kudela, T. Terebessy, M. Kando, Appl. Phys. Lett. **76**, 1249 (2000).
[7] T. Terebessy, M. Kando, J. Kudela, Appl. Phys. Lett. **77**, 2825 (2000).
[8] T. J. Wu, W. J. Guan, C. M. Tsai, W. Y. Yeh, C. S. Kou, Phys. Plasmas **8**, 3195 (2001).
[9] T. Terebessy, M. Sirý, M. Kando, J. Kudela, D. Korzec, Appl. Phys. Lett. **82**, 694 (2002).