Radial profile of the electron energy distribution function in RF capacitive gas-discharge plasma

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Abstract. This paper reports experimental results on low-pressure argon capacitive RF discharge (parallel-plate capacitively-coupled plasma – CCP) under different conditions, namely, gas pressure in the range 3 – 30 Pa and RF power in the range 10 – 100 W. The IV characteristics measured were processed by two different second-derivative probe techniques for determination of the plasma parameters and the electron energy distribution function. The radial profiles of the main plasma parameters are presented.

1. Introduction
Low-temperature (non-equilibrium) plasmas are the basis of a number of technologies, old, current and future. The success story is, of course, plasma etching, which, together with photo-lithography, is the basis for miniaturization of integrated circuits; other major applications include surface alloying, thin-film deposition, plasma displays, modification of the properties of polymers and organic materials. Recently, the most promising has seemed to be the field of plasma-based medical applications. However, non-equilibrium plasmas are difficult to describe by universal theories, so that joint efforts are needed in diagnostics and modelling in order to understand their properties and use that knowledge to control, design and optimize applications. The importance of the research is that it will facilitate applications while focusing the scientific effort on the fundamental aspects of non-equilibrium plasmas [1]. Joint experimental and modelling efforts are required to make any general, fundamental conclusions about non-equilibrium plasmas.

This paper reports experimental results on studying a capacitive low-pressure argon RF discharge for a range of conditions [2], such as gas pressure in the range 3 – 30 Pa and power ranging from 10 W to 100 W. The current-voltage (IV) characteristics obtained by a Langmuir probe were processed by two different second-derivative probe techniques [3] to determine the plasma parameters and the electron energy distribution function.

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electron energy distribution function (EEDF). The radial profiles of the main plasma parameters were also constructed.

2. Langmuir probe measurements in a RF capacitively coupled system

The RF system consisted of a chamber with parallel plate electrodes powered by a RF source with a driving frequency $f = 13.56$ MHz. The discharge in this experiment was ignited at an electrode distance of 0.07 m between the top powered and the bottom grounded electrode both with a diameter of 0.11 m. The transmitted RF power was measured at the source and always stayed below 1 % of transmitted power. A Hiden’s ESPION Langmuir probe system with a motion stage was used to measure the $IV$ characteristics. The probe tip with a diameter of 0.15 mm and a length of 10 mm was placed in the plasma with the motion stage allowing motion along the radial direction at $L = 0.02$ m above the bottom electrode. The $IV$ characteristics’ data were recorded using the ESPION software and then exported for further analysis.

In the “classical regime”, which corresponds to our experimental conditions, the probe operates in the absence of a magnetic field and at low gas pressures in the range of 0.1 Pa to 100 Pa [4]. Then the electron probe current of the $IV$ characteristic is expressed by the well-known formula [4]:

$$I_e(U) = \frac{2\pi S}{m^2} \int_{-\infty}^{\infty} (W - eU)f(W)dW,$$

(1)

where $e$ and $m$ are the electron charge and mass, $S$ is the probe area, $W = \frac{1}{2}mc^2 + eU$ is the total electron energy in the probe sheath and $c$ is the electron velocity. Here the probe is negatively biased by a potential $U_p$, and $U$ is the probe potential with respect to the plasma potential $U_{pl}$ ($U = U_p - U_{pl}$). $f(\varepsilon)$ is the isotropic electron energy probability function (EEPF) [1], normalized by:

$$\frac{4\pi\sqrt{2}}{m^{3/2}} \int_0^{\infty} f(\varepsilon)\sqrt{\varepsilon}d\varepsilon = \int_0^{\infty} f(\varepsilon)d\varepsilon = n.$$

(2)

The EEPF can be determined by using the Druyvesteyn’s formula [5]:

$$f(\varepsilon) = \frac{2\sqrt{2m}}{eS} \frac{d^2I_e(U)}{dU^2}.$$

(3)

The second derivatives obtained from the measured $IV$ characteristics were evaluated by two techniques. The first one consists in adjacent averaging, smoothing and differentiating twice the measured $IV$ characteristics. The instrumental function of the differentiation technique is triangular with a half-width equal to the step of change of the probe bias [6]. The other differentiating technique is based on the convolution of data with an adaptive, differentiating filter, whose instrumental function is automatically adjusted so that noise and distortion, i.e., error, are locally kept at about the same level. Details on how noise and distortion can be readily evaluated can be found in [3], as well as in the references therein. In this work, as before, we continue using $(1 + \cos(\ldots))$ kind of filters for their flexibility on how the full-width-to-half-maximum (FWHM) can be adjusted to run-time, hence how readily the noise-to-error ratio can be kept constant.

Figures 1 and 2 represent examples of the EEDFs evaluated at the center of the discharge chamber at 50 W discharge power and gas pressure of 6 Pa and 27 Pa. The solid black lines present results from direct differentiation. The distortions between 0 and 10 eV cannot be explained by the influence of the differentiation method’s instrumental function and the probe size [6]. A possible reason of the appearance of additional distortions is the insufficient ratio $\Sigma$ between the surface area of the measuring ($S_p$) and reference ($S_r$) probes of the HIDEN probe circuit. Usually, it is accepted that it has to be:
\[
\Sigma = \frac{S_p}{S} > \sqrt{\frac{M}{m}}. \tag{4}
\]

Here \( M \) is the ion mass. For precise measurements, a more severe criterion for the ratio \( \Sigma \) must be used [7]:

\[
\sum = \frac{S_p n_p (T_p)^{1/2}}{S_r n_r (T_r)^{1/2}} G_\alpha \geq 10^4. \tag{5}
\]

In this equation, \( T \) and \( n \) are the electron temperatures and densities at the positions of the measuring (p) and reference (r) probes. The factor \( G_\alpha \) is tabulated in [7] for different probe and reference probe geometries.

On the other hand, the reference probe is flush mounted on the probe holder (close to the probe tip) with surface area not enough to satisfy the condition (5). To compensate for the insufficient ratio \( \Sigma \) in the second technique, an effective resistance \( R_{eff} \) was added to the probe circuit. Results with \( R_{eff} = 200\ \Omega \) (red curve) and \( R_{eff} = 500\ \Omega \) (blue curve) are presented in figure 1. As the effective resistance \( R_{eff} \) is increased, the EEDF evaluated approaches the Maxwellian with an electron temperature of 5 eV up to the energy of the first excited level of argon (11.56 eV). At higher energies, the EEDF deviates from Maxwellian due to the inelastic electron-atom collisions and the non-equilibrium nature of the discharge. We should point out that the distortions of the blue curve in the range 0 \( \sim \) 3.5 eV correspond to the distortions due to the instrumental function and the influence of the probe size [6].

The same considerations are related to the results recorded at a higher pressure presented in figure 2. Here, the effective resistances are \( R_{eff} = 2k\ \Omega \) (red curve) and \( R_{eff} = 5k\ \Omega \) (blue curve). It can be seen that the blue curve is not appropriate. The electron temperature in this regime of the discharge is 6 eV.

We have to point out that to solve the problem mentioned above, additional experiments with different reference probe areas are planned for the near future.

**Figure 1.** EEPF obtained by direct differentiation of the measured \( IV \) (solid black line); red curve – obtained by introducing a 200 \( \Omega \) effective resistance in the probe circuit; and the blue curve, 500 \( \Omega \).

**Figure 2.** EEPF obtained by direct differentiation of the measured \( IV \) (solid black line); red curve – obtained by introducing a 2k \( \Omega \) effective resistance in the probe circuit; and the blue curve, 5k \( \Omega \).
3. Experimental results
Below we present the main plasma parameters evaluated from the $IV$ characteristics measured at different radial positions. The radial distributions of the plasma potential at different discharge RF power values and different gas pressures are presented in figures 3 a) and 3 b). The accuracy of the evaluation is $\sim 10\%$. In figure 3, the $U_{pl}$ is higher at the center of the discharge. This effect is more pronounced at higher gas pressures (figure 3 b)). At lower pressures, the $U_{pl}$ is almost constant. The dashed lines indicate the size of the electrodes. As the discharge power is increased, the plasma potential values increase by about 10 V.

![Figure 3. Radial distributions of the plasma potential at different discharge RF power values and different gas pressures.](image)

As we mentioned, the EEPF can be approximated by a Maxwellian distribution up to the energy of the first excited level of argon. An example of the resulting electron temperatures are presented in figure 4 a), b).

![Figure 4. Radial distributions of the electron temperatures at different discharge RF power values and different gas pressures.](image)
Figure 5 shows the corresponding radial profiles of the electron densities at different discharge RF power values and different gas pressures.

![Figure 5](image)

**Figure 5.** Radial distributions of the electron densities at different discharge RF power values and different gas pressures.

4. Conclusions
This paper reports experimental results on a capacitive low-pressure argon RF discharge at different conditions, as gas pressure in the range $3 \div 30$ Pa and RF power within $10 \div 100$ W.

The current-voltage ($IV$) characteristics measured were processed by two different second derivative probe techniques for determination of the plasma parameters and the electron energy distribution function (EEDF). The radial profiles of the plasma potential and the electron temperatures and densities at different discharge RF powers and different gas pressures are presented.

Acknowledgements
This research has been supported by the JOINT RESEARCH PROJECTs between the Academy of Sciences and Arts of Serbia (SASA) and the Institute of Electronics BAS BG, and the Portuguese FCT – Fundação para a Ciência e Tecnologia, under Project UID/FIS/50010/2013. Additional funding for experiment is provided by SASA project 155 and MPNTR of Serbia ON171037 and III41011.

References
[1] Godyak V A and Demidov V I 2011 *J. Phys. D: Appl. Phys.* **44** 233001
[2] Godyak V A, Piejak R B and Alexandrovich B M 1992 *Plasma Sources Sci. Technol.* **1** 36-58
[3] Dias F M and Popov Tsv K 2007 *J. Phys.: Conf. Series* **63** 012005
[4] Demidov V I, Kolokolov N B and Kudriavtsev A A 1996 *Probe Methods of Diagnostics of Low Temperature Plasma* (Moscow: Energoatomizdat) (in Russian)
[5] Druyvesteyn M J 1930 *Z. Phys.* **64** 781-98
[6] Popov Tsv K, Dimitrova M, Dias F M, Tsaneva V N, Stelmashenko N A, Blamire M G and Barber Z H 2006 *J. Phys.: Conf. Series* **44** 60–9
[7] Chang J-S 1973 *J. Phys. D: Appl. Phys.* **6** 1674