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Plasma parameters of argon and argon/molecular gas mixture plasmas produced in microwave discharge

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ABSTRACT

The experimental results and their analysis are presented concerning electron density and temperature of the microwave discharge plasma (power range 100–500 W) produced in Ar gas and Ar–N_2 and Ar–N_2–NO gas mixture at the total pressure of 0.5 Torr. The triple probe method was primarily used in order to set-up a direct and on-time technique to measure electron temperature in complex plasma. The results were compared with those obtained using a cylindrical probe mounted in a circuit with reference electrode. Each probe was made of tungsten wires of 0.5 mm diameter and 3 mm in length each. When plasma contains only one maxwellian group of electrons, within the experimental errors, both the probes systems get comparable value of plasma parameters. When the characteristic of cylindrical probe shows two groups of thermal electrons within the microwave plasma the triple probe may show always results concerning one group but of which temperature depends on the ratio of the densities of those two groups of electrons.

1. Introduction

The microwave plasma discharges (MPDs) generate energetic electrons with the temperature much higher than gas temperature, which by inelastic collisions can excite and ionize atoms and dissociate molecules, while some electronegative atoms or molecules may form negative ions by attachment of low energy electrons [1,2]. For this reason the MPDs are intensively used for various applications such as film deposition [3], destruction and removal of gaseous pollutants [4] and ion or molecular sources [5]. One of the key problems in any of these plasma applications or studies of the microwave plasma properties is plasma diagnostic. Due to their relative simplicity in measuring the local values of basic plasma parameters as electron temperature and density the electrical probe methods and techniques are most used. But, basically the microwave plasma discharge is an electrode-less system, so that the use of any plane, cylindrical or spherical Langmuir probe technique is not just straightforward, while it needs a reference electrode. Consequently, the floating probe system has to be used [6] but, in most cases, the presence of a large surface electrode as reference in the probe circuit may determine the mismatch of plasma-microwave powered system. Moreover, the reference electrode coupling with plasma volume may not be stable and probe characteristics are changed by probe circuit and not by plasma properties. These difficulties might be overcome using either double probe system [7] or triple one [8]. The theoretical models of both double and triple probe are based on similar assumptions as Langmuir probe and provide similar results when electron velocity (or energy) distribution function (EEDF) is a maxwellian one [9]. But, the EEDF of various discharge plasmas, including microwave one, might be non-maxwellian, which often is described as convolution of two maxwellian groups of electrons [10] usually named as fast or hot electrons characterize by temperature T_{ef} and slow or cold electrons with temperature T_{es}, respectively ($T_{ef} > T_{es}$) [11].

On the other hand, the double or triple probe currents consist of ion component and only a small fraction of electron current might be involved, intensity of which is comparable with ion saturation current intensity [8,9]. Consequently, in most cases this fraction includes mainly fast electrons but, as it will be later seen, this does not necessarily means that the electron temperature measured by double or triple probe corresponds to T_{ef}. From the practical point of view the triple probe method is more suitable than the double probe method because the triple probe can provide us with direct reading of the electron temperature [8]. Moreover, the triple probe method can be also used directly for diagnostic of pulsed or non-stationary plasma.

In present paper the electron temperature of microwave plasma discharge is measured by triple probe which allows almost direct reading of electron temperature, using a very simple circuit, and

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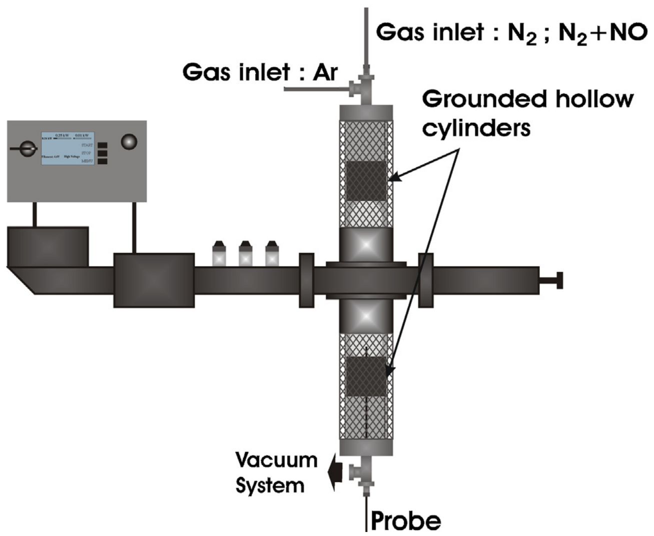

Fig. 1. Schematic representation of the experimental device used in microwave plasma parameters determination.

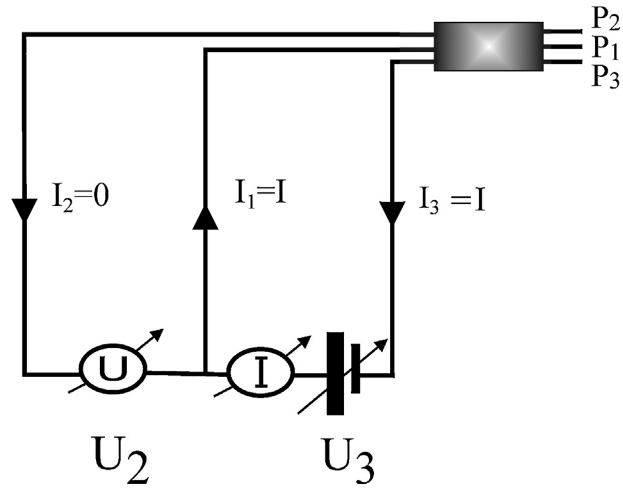

Fig. 2. The triple probe measurements circuit. Adapted from reference [8].

compared with the temperature measured by cylindrical Langmuir probe. The electron temperatures and densities are measured versus microwave power transferred to plasma produced in different gases or gas mixtures such as Ar, Ar–N_2 and Ar–N_2–NO and total gas pressure of 0.5 Torr but various partial gas pressures of the components. Taking into account that triple probe model is based on presence of one maxwellian group of electrons the standard cylindrical Langmuir probe was used in order to check also the EEDF and experimental conditions in which the triple probe method can be used [12–17].

2. Materials and methods

The experimental device is presented in Fig. 1. The microwave discharge is produced by the SAIREM BMP Ked B (2.45 GHz) generator attached to a surface waveguide and a cylindrical quartz discharge tube (diameter of 5 cm and 40 cm in length) locally surrounded by applicator waveguide of the microwave system. The Ar, N_2 and/or the N_2–NO gas mixtures are continuously injected in the discharge tube under a constant flux of 80 ml/min using a mass flow controller and a rotary vane pump. The various percentages of N_2 or N_2–NO were added to Ar gas in the total gas flow mixture. Moreover, standard N_2–NO gas mixture, in which 40 ppm of the NO component diluted in nitrogen were used so that, the final NO concentration within gas discharge mixture was between 1 ppm (for 2.5% (N_2 + NO)) to 4 ppm (for 10% (N_2 + NO)). The total pressure was fixed at 0.5 Torr and the microwave power was in the range of 100–500 W (reflected power less as 10 W).

The electron temperature and density were measured using a cylindrical probe [9,18] and a triple probe inserted on the axial direction of the discharge tube at 6 cm distance from the applicator waveguide. The cylindrical probe consists of a tungsten wire of 0.5 mm in diameter and 3 mm in length mounted inside the hollow ceramic insulator shaft. The triple probe system consists of three identical tungsten cylindrical probes (0.5 mm diameter and 3 mm length each, mounted parallel in 2 mm distance each other) supported by the three bore ceramic insulator shaft.

The cylindrical probe was immersed in the plasma volume and the probe current intensity was measured as the voltage drop across a resistor of $R = 33\,\Omega$. The *I*–*V* probe characteristics are acquired on the TDS5034B Tektronix oscilloscope and then smoothed and processed using data analysis software in order to determine the electron temperature and density using the standard procedure [9].

3. Theory

3.1. Single Langmuir probe

The single electrostatic probe method proposed by Mott-Smith and Langmuir in 1926 [18] remains certainly one of the most convenient method to determine both the electron temperature and density. The main assumption is that the probe does perturb the plasma only locally as collisionless sheath region around the probe. This can by justified by the fact that the Debye length is much lower than electron mean free path. For electron temperature T_e between 1 eV and 7 eV and electron density n_e in the range 10^{11}–10^{12} cm^{-3}, the Debye length is in the range 3.3×10^{-6}–6.1×10^{-5} m, which is about two order of magnitude smaller than electron mean free path ($\lambda e = 1/(n\sigma)$) [19], where n is the argon density and σ the mean electron–neutral collision cross section), that is in the range 5 mm–0.4 mm for an argon pressure of 0.5 Torr.

Moreover, due to low Debye length the sheath thickness is also much smaller comparing with probe diameter so that particles orbital motion around the probe might be neglected.

3.2. Triple probe

The triple method consists in measuring the plasma parameters using the system of three identical cylindrical probes, placed within homogenous and isotropic plasma volume. The electrical circuit is presented in Fig. 2. The V_1, V_2 and V_3 potentials of each probe with the respect to local space potential V_s are presented in Fig. 3. The floating potential V_f is the same for any probe of the system. The external biased voltage U_3 was applied between one pair of probes (probe P_3 biased negatively with respect to the probe P1 in Fig. 2) and the current intensity I of the circuit and the potential U_2 of the probe P_2 with respect to the same reference probe P_1 were measured as shown in Fig. 2.

By setting $U_3 = V_3 - V_1$ sufficiently large (in this case around −40 V) the current intensity I of the P_3 and P_1 probes circuit corresponds to ion saturation one and the U_2 (= $V_f - V_1$) potential becomes the floating potential of the P_2 probe measured with