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Study of magnetic field influence on charged species in a low pressure helicon reactor

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The variation of electron density (n_e), ion flux and emission of argon lines were investigated in a rf helicon reactor for different static magnetic field amplitude and rf power using Langmuir probe, rf coupled planar probe and optical emission spectroscopy (OES). The static magnetic field was created by two Helmholtz coils positioned around the plasma source. Its amplitude B varied by changing the current $I_B = 0 \div 2$ A through the coils from 0 to 10 mT ($0 \div 100$ Gauss) in the helicon source, which corresponded to $0 \div 1.4$ mT ($0 \div 14$ Gauss) in the diffusion chamber. We studied Ar and O_2 discharges at 0.7 Pa with rf power $50 \div 600$ W applied to the helicon antenna. The variations of n_e, ion flux and intensity of Ar 750 nm with the rf power measured in Ar diffusion plasma were in a good agreement. It was found that n_e increased monotonically with the rf power for $I_B < 1$ A whereas for higher current it exhibited a maximum, which position shifted from lower to higher rf power with increasing I_B. The OES measurements in the plasma source for $I_B = 1.5$ A showed that the Ar emission line did not reach a maximum but continuously increased with the rf power. Hence, it is concluded that the maximum observed for n_e in the diffusion chamber is likely to be due to some confinement of the plasma in the source. Measurements in oxygen discharge showed slightly different results.

PACS: 52.50.Qt
Key words: helicon reactor, argon, oxygen, electron density, ion flux

1 Introduction

Helicon generation of plasmas was first employed by Boswell [1], following years of helicon propagation studies and applications in material processing (e. g. [2]). Helicons are propagating whistler wave modes in a finite diameter, axially magnetized plasma column, excited by an rf driven antenna that couples to the transverse mode structure across an insulating source wall [3]. Beside the wave coupling, two other coupling modes, capacitive and inductive, can be ignited in the source for certain input rf power and magnetic field [4].

Helicon applications to material processing utilize a process diffusion chamber downstream from the source. The present paper is focused on an investigation of the rf helicon reactor used for material processing, namely on an influence of dc magnetic field and rf power on the discharge parameters in the diffusion chamber. The reactor was previously used for the deposition of silicon oxides and organosilicon polymer films as well as plasma diagnostics [5]. It was, however, equipped with one magnetic coil around the source tube whereas here, two coaxial coils producing more homogeneous axial magnetic field were used. This study resumes on early results on the effect of the magnetic field on the discharge generated by the one–coil source [6] and deals with non–depositing gases only because of difficulties met in deposition conditions.

2 Experimental

The studied helicon reactor consisted of the helicon source made of a 30 cm long glass tube, 15 cm in diameter, and the stainless steel diffusion chamber with the length and diameter, both of 30 cm [5, 6]. The source tube was surrounded by two Helmholtz coils supplied by a dc current of $0 \div 2$ A. The continuous wave rf power (13.56 MHz) in the range $50 \div 600$ W was applied to the helicon antenna through an L–type matching box. Argon (Ar) or oxygen (O_2) were injected through a small tube above the source directly to the source tube. Pressure was in both cases 0.7 Pa.

The magnetic field lines were parallel to the reactor axis in the source and diverged in the diffusion chamber [5]. Compared to the one–coil source [5, 6] the amplitude of the axial magnetic field created by the two Helmholtz coils was more uniform. Calculations of this amplitude (B) showed that varying the current (I_B) in the coils from 0 to 2 A corresponded to $B = 0 \div 10\,\mathrm{mT}$ ($0 \div 100$ Gauss) in the source tube and $0 \div 1.4$ mT ($0 \div 14$ Gauss) in the diffusion chamber (Fig. 1).

The discharge in the diffusion chamber was investigated by a commercial cylindrical rf compensated Langmuir probe (SmartProbe). It was assumed that the weak magnetic field did not influence the measurement. Since future experiments are

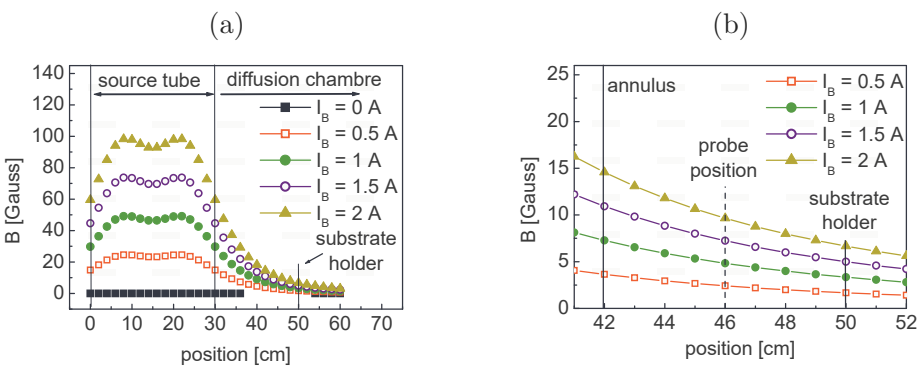

Fig. 1. Calculations of the axial magnetic field in dependence on the current through the coils (I_B): (a) – whole reactor, (b) – detail of the diffusion chamber.

planned to be performed in deposition mixtures (such as O_2/hexamethyldisiloxane) the results from the Langmuir probe were compared with a rf driven planar probe that is not affected by the deposition of thin dielectric film [7]. Both the probes had their active area in the center of the chamber, 15 cm under the source tube orifice and 4 cm above the substrate holder. The principle of the planar probe is as follows. The probe is rf biased through a capacitance and a dc self–bias appears on its surface. When the rf voltage is switched off, only ions can reach the probe. The variation of probe voltage with time is then linked to the ion flux [7]. Our probe consisted of a concentric central disc (7 mm in diameter) and an outer guard ring (16 mm in outer diameter).

Additionally to the probe measurements, optical emission spectra were recorded using a fiber optics and a Jobin Yvon HR640 monochromator equipped with Hamamatsu R928S photomultiplier through quartz windows at two positions: at the top of the source tube in the reactor axis and in the mean height of the diffusion chamber. In our measurement we focused on Ar emission line at 750 nm that can be used as a measure of electron density under the assumptions of (a) direct electron excitation and (b) constant electron temperature. In O_2 discharge, 5 % of Ar was added to pure O_2 in order to observed Ar emission line too.

3 Results and disscussion

Langmuir probe characteristics revealed that the electron energy distribution could be approximated by Maxwellian in Ar as well as in O_2. Therefore both, electron density and temperature, were evaluated from these measurements. The electron temperature in the diffusion chamber of Ar discharge was about 3.2 eV for all input powers of $I_B = 1.5$ and 2 A. For weaker magnetic fields ($I_B \leq 1$ A), the electron temperature decreased strongly from about 3.2 eV for 25 W to 2.7 eV for 150 W and stayed constant for higher input powers. The electron temparature in the diffusion chamber of O_2 discharge decreased continuously with the input power from 3.8 eV to 2.8 eV for $I_B < 1$ A. For $I_B \geq 1$ A the electron temperature stayed

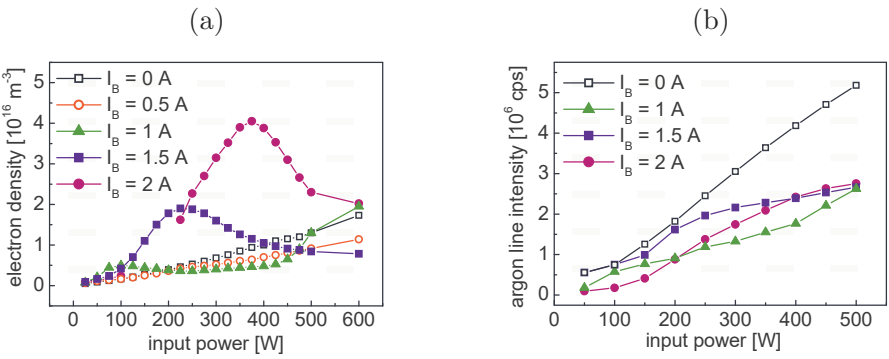

Fig. 2. Dependencies of (a) electron density in the diffusion chamber and (b) intensity of Ar emission line (750 nm) in the source tube at 0.7 Pa on rf input power for different current to the coils I_B in argon discharge.

constant around 4 eV.

The dependence of electron density in the diffusion chamber of Ar discharge on the rf input power for different current to the coils (I_B) is shown in Fig. 2a. The electron density increased monotonically with the input power when a weak magnetic field was applied ($I_B < 1$ A). For more intensive magnetic field ($I_B \geq 1$ A), the electron density exhibited a maximum which position and magnitude changed with I_B. It reached 4×10^{16} m^{-3} at 350 W for $I_B = 2$ A and 2×10^{16} m^{-3} at 200 W for $I_B = 1.5$ A. For $I_B = 1$ A, a very weak maximum of 4×10^{15} m^{-3} appeared at 100 W.

Assuming a direct electron excitation and a weak dependence of the electron temperature on the rf power (see above), the intensity of Ar emission line at 750 nm is proportional to the electron density. The dependencies of Ar emission on rf power in the source tube are shown in Fig. 2b. For $I_B < 1$ A, the intensity increased almost linearly and these results are comparable to the electron density measurements in the diffusion chamber. For $I_B = 1.5$ and 2 A, it increased strongly when increasing the rf power from 100 W to 250 W and from 100 W to 400 W, respectively, which corresponded to the same behavior of the electron density in the diffusion chamber. For higher input power the intensity increased weakly in the source whereas the electron density measured in the diffusion chamber strongly decreased.

To confirm the results of the Langmuir probe in the diffusion chamber we compared the electron density with ion flux measured by planar probe and intensity of Ar emission line. The comparison for Ar discharge without magnetic field ($I_B = 0$ A) and for $I_B = 1.5$ A is given in Fig. 3a and b, respectively. All three diagnostics methods were in good agreement. In addition, the ion saturation flux taken from the Langmuir probe measurement was in good agreement with the ion flux measured by the planar probe. Similar agreement was achieved for O_2 discharges. Since the same trends were observed for all charged and excited particles in the diffusion chamber the results are quite reliable.

The trends in O_2 discharge are shown Figs. 4a and 4b. The electron density increased strongly with the input power for all I_B except 1 A where a plateau

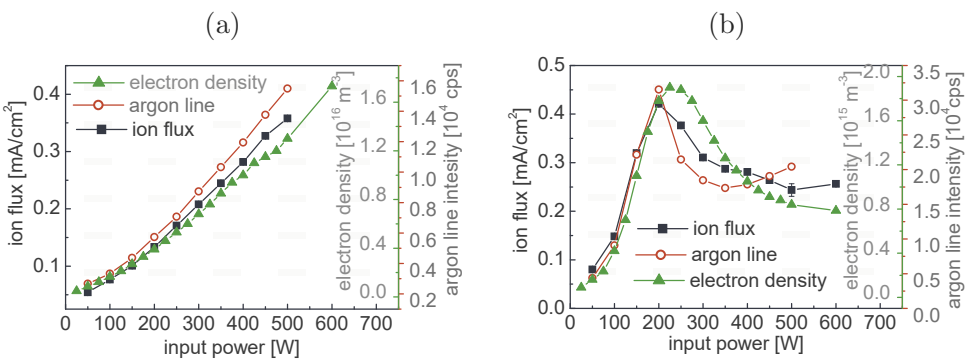

Fig. 3. Comparison of the variations of the electron density, ion flux and Ar 750 nm line intensity with the rf power at 0.7 Pa for $I_B = 0$ A (a) and $I_B = 1.5$ A (b) in Ar discharge.

of about $7 \times 10^{15}\,\mathrm{m}^{-3}$ was observed from 400 W (Fig. 4a). For low input power (< 100 W) the magnitude of the electron density was almost independent of I_B. The maximum density of about $1.1 \times 10^{16}\,\mathrm{m}^{-3}$ was obtained for $I_\mathrm{B} = 1.5$ A. The intensity of Ar emission line in the source, showed for $I_\mathrm{B} = 1$ A in Fig. 4b, exhibited similar dependence on rf power as the electron density in the diffusion chamber.

In order to propagate the helicon waves in the helicon reactor the power exceeding 1.5 kW is needed [8]. It was, however, impossible to reach it for our continuous wave mode due to extreme heating dangerous for the source tube. Such high power could be used only in a pulse mode. Therefore, it is assumed that the helicon mode was not coupled in the power range used in the present study. Only the capacitive or inductive coupling was possibly present [4].

The behavior of electron density observed especially in the diffusion chamber of Ar discharge is more likely due to some confinement of the plasma in the source, maybe due to magnetic field gradients at the source exit which prevents the diffusion. The diffusion coefficient $D_{\|}$ parallel to the magnetic field vector (and parallel to the reactor axis) is not influenced by magnetic field. The diffusion coefficient perpedicular to the magnetic field can be calculated as [9]

$$D_\perp = \frac{D}{1 + {\omega_\mathrm{c}}^2 \tau^2}\,, \tag{1}$$

where ω_c is electron cyclotron frequency, τ^{-1} is mean collision frequency and D standard diffusion coefficient. The diffusion coefficient $D_\perp$ calculated from (1) using a reference data of electron to Ar collision cross–section [10] vary in the range from 1 to $0.0005 \times D$ for $I_\mathrm{B} = 0 \div 2$ A, assuming an homogenous magnetic field and electron temperature around 3 eV. Similarly, the electron to O_2 collision cross–section taken from [11] gives the diffusion coefficient $D_\perp$ in the range from 1 to $0.0007 \times D$ for $I_\mathrm{B} = 0 \div 2$ A. The electron mean free paths calculated from the same data were about 12 cm and 8 cm for Ar and O_2 discharge, respectively. These values are comparable to the reactor dimensions.

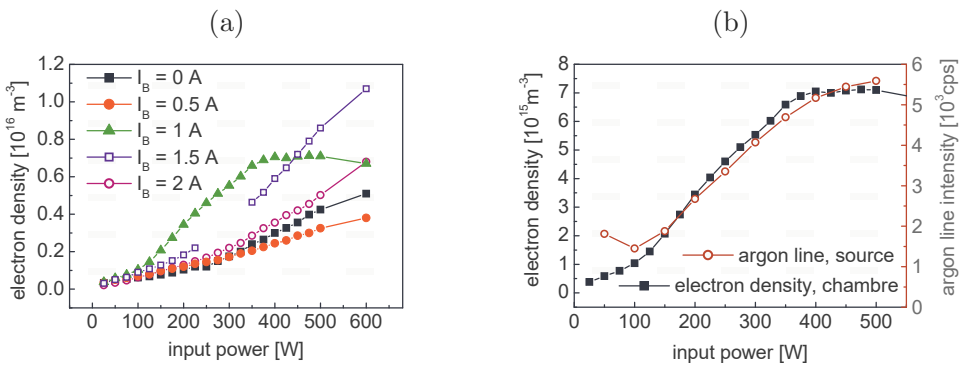

Fig. 4. Dependencies of (a) electron density in the diffusion chamber and (b) intensity of Ar emission line at 750 nm in the source on rf power for different current to the coils I_B at 0.7 Pa in O_2 discharge.

4 Conclusion

The variation of the electron density and ion flux measured by the Langmuir probe, the ion flux measured by the rf coupled planar probe and emission of argon line in the diffusion chamber of helicon reactor were in very good agreement. Therefore, any of these three techniques can be used for a study of plasma parameters. This is an important information for future investigation of deposition processes in the same reactor.

In Ar and O_2 discharge, the intensity of Ar emission line (a small amount of Ar was added to O_2) in the helicon source did not present any maxima but continuously increased with the rf power. The electron density in the diffusion chamber of Ar discharge increased with the rf power for $I_B < 1$ A, i. e. low magnetic field, whereas for higher current it exhibited a maximum, which position shifted from lower to higher rf power with increasing I_B. These maxima were likely due to a plasma confinement in the source created by the magnetic field. The electron density measured in O_2 discharge did not show any maxima with the rf power. It increased strongly with the input power for all I_B except 1 A where a plateau was observed.

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