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Laser photodetachment diagnostics of electronegative expanding plasmas

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Abstract. The study presents results from measurements of the negative hydrogen ion density by laser photo-detachment in the expanding plasma region of an inductively-driven tandem plasma source. The results obtained show that the negative ion density and the plasma electronegativity increase with increasing the high-frequency power absorbed in the discharge. An optimum gas pressure range [(1-3) Pa] for negative ion production in the expansion chamber is observed.

1. Introduction

The application of inductive plasma sources in the semiconductor industry for surface modification, etching, cleaning and thin film deposition [1], especially with electronegative working gases, requires investigation and optimization of the operational regime with respect to the density of the negative ions. Optimization of the inductive ion sources [2] for effective production of negative hydrogen ions is also a key problem for neutral beam heating of fusion devices. Probe and laser photodetachment methods are widely used for measurements of the negative ion density n_- in electronegative plasmas. The first one is based on determination of n_- from the current-voltage probe characteristic and its derivatives but the method is applicable to discharge plasmas [3, 4] with high electronegativity, i.e. high values of the (n_-/n_e)-ratio, where n_e is the electron density. The second method is based on photodetachment of electrons from the negative ions by laser irradiation and their subsequent detection by different techniques: microwave cavity, electrical probe or optogalvanic detection [5]. The laser photodetachment diagnostics [5, 6] assisted with electrical probes allows measurements of very low electronegativity (<1%).

The tandem type plasma source studied here driven by an inductive discharge at 27 MHz has been extensively investigated [7-11], both in argon and hydrogen, in view of applications in plasma technologies and as a negative ion source. The plasma produced in the driver region of the source expands in a larger second chamber. The electron energy distribution function and the spatial distribution of the plasma parameters measured by probe diagnostics in the expansion region show an electron cooling and a decrease of the electron density with the distance from the driver region. The decrease of the number of electrons with high energy away from the driver ensures proper conditions for negative ion production in hydrogen discharges.

The study provides results on the negative hydrogen ion density in the expanding region of a tandem plasma source obtained by applying the photodetachment technique. In the experiment, the gas pressure and the high-frequency (HF) power absorbed are varied. Existence of an optimal pressure range for negative ion production and an increase in the negative ion yield with the power are shown.

2. Experimental set-up

The experimental set-up (figure 1) is a tandem type plasma source (see [11] for more details). In brief, a 9-turn coil inductively couples the HF power (at 27 MHz) to the discharge produced in a quartz tube (4.5 cm in diameter and 30 cm in length). The plasma expands in a larger metal chamber (with radius of 11 cm and length of 47 cm). The working gas is hydrogen. The negative ion concentration is measured in the expansion region by employing the laser photodetachment technique. The second harmonic radiation (532 nm) of a Nd:YAG laser (Surelite III-10) irradiates the plasma and a tungsten probe (length of 1 cm, 0.4 mm diameter), coaxial to the laser beam, is used to detect the photodetached electrons (figure 2). The laser beam diameter in the plasma column is limited by a diaphragm, 1 cm in diameter, positioned at the laser beam entrance to the chamber. The laser pulse length is 4 ns. The measurements are performed with the laser beam power (~100 mJ) at which the photodetachment current I_{ph} from the probe is practically saturated and, thus, the relation

$$\frac{I_{ph}}{I_{dc}} = \frac{\Delta n_e}{n_e} = \frac{n_-}{n_e} \tag{1}$$

for determination of the negative ion density [5] is fulfilled. Here I_{dc} is the electron saturation current at probe potential well above the plasma potential and Δn_e is the density of the released electrons from photodetachment of negative ions.

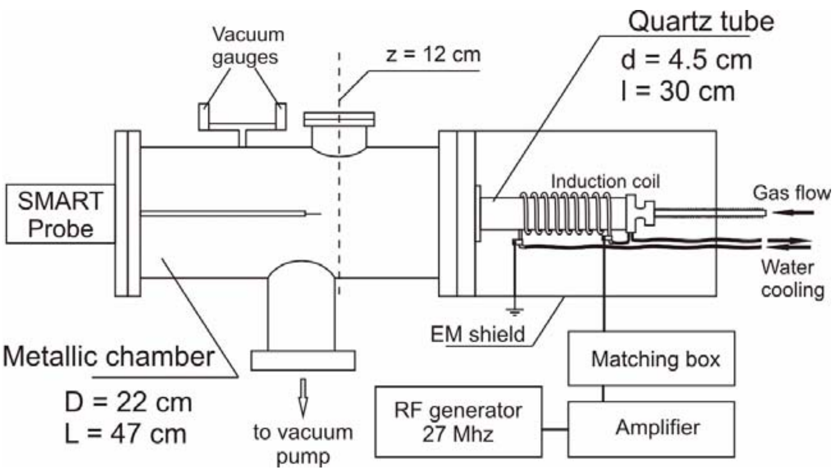

Figure 1. Schematic representation of the experimental set-up. The position z = 12 cm where the measurements are performed is marked.

The probe is biased with respect to the metal chamber by batteries (up to 80 V). The DC probe current is registered as a voltage drop over a 150 Ohm resistor and the AC component of the signal due to the electrons from the photodetachment is separated by a 1 μF capacitor and measured over a 50 Ohm resistor. The photodetachment signal is measured by a digital storage oscilloscope Tektronix TDS360. To suppress the electrical noise, inherent to HF discharges, a rf choke filter tuned at the driving frequency and two low pass filters with a cut-off frequency of 10 MHz are incorporated in the probe electrical circuitry. The plasma parameters in the expansion region are measured by a SmartProbe^{TM} probe system. The probe tip of the system is a tungsten wire with length of 1 cm and diameter of 0.38 mm and the probe is movable along the axis of the metal chamber. The system has a built-in passive compensation of the noise and each probe characteristics is obtained by averaging over 45 probe voltage sweeps.

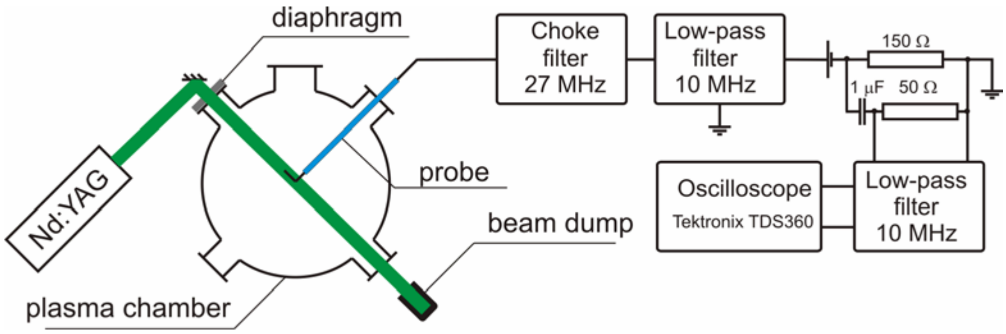

Figure 2. Experimental set-up of photodetachment and probe diagnostics. The plasma chamber is shown in a crossectional view.

3. Results and discussion

The energy of the laser beam is fixed at such a level that the photodetachment current is saturated. Ablation peak in the signal due to direct laser irradiation of the tungsten probe tip is observed with further increase of the laser energy (figure 3).

Saturation of the photodetachment current is reached and a well pronounced plateau is observed when the laser beam diaphragm has a large enough diameter and, thus, the ratio I_{ph}/I_{dc} can be measured more accurately. In our case it is found that a 10 mm diaphragm is sufficient to ensure validity of (1). The electronegativity in the expansion region of the tandem plasma source in hydrogen discharge at an axial position z = 12 cm away from the quartz tube end is measured in a wide pressure range [p = (0.3 – 5) Pa] at HF power varied between 200 W and 700 W and is presented in figure 4. It increases with the HF power and shows a weak dependence on the neutral gas pressure.

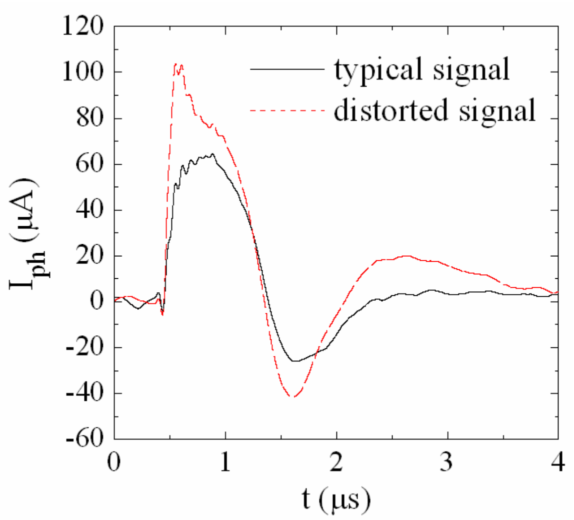

Figure 3. A comparison of typical and distorted photodetachment signals obtained at low and high laser pulse energies.

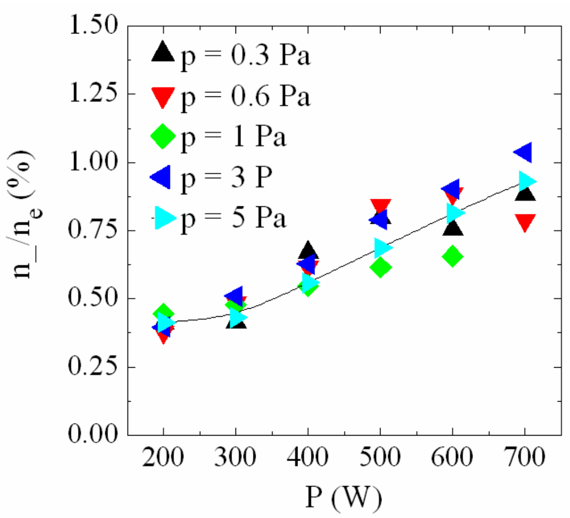

Figure 4. The measured electronegativity for different pressures as function of the absorbed power.

In order to obtain the negative ion density, the electron density n_e at the same position is also measured. Its dependence on the pressure is non-monotonous (figure 5), with a formation of a maximum at (1-3) Pa. The decrease of n_e at the high pressures is in agreement with the results obtained away from the driver (z = 12 cm as here) in earlier experiments [7, 11], both in argon and hydrogen. Despite of the n_e-increase in the driver with the gas pressure, the electron density in the expanding plasma volume decreases due to lowering of the transport coefficients. On the other hand, the decrease of n_e at the low pressures may be related to the lowering of n_e in the driver when the gas pressure is low.

The negative ion density behaviour with the variation of neutral gas pressure (figure 6) is similar to the n_e-behaviour. Its value reaches a maximum in the range p ≈ (1-3) Pa which appears as an optimum pressure range for negative ion production. The dependences of the negative ion density on

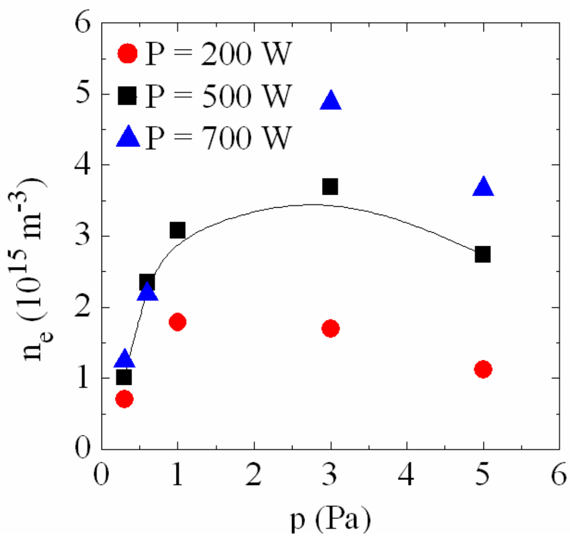

Figure 5. Dependence of the electron concentration on the neutral gas pressure.

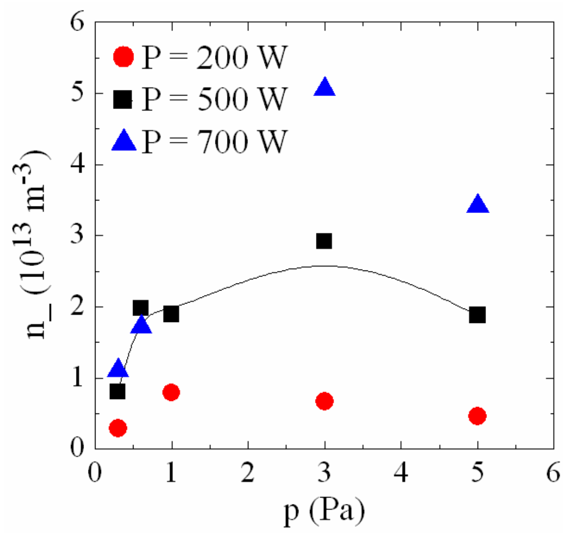

Figure 6. Dependence of the obtained negative hydrogen ion density on the pressure.

the gas pressure and on the absorbed HF power correlate with those of the electron density, but the behaviour of the negative ions is more complicated due to the various processes involved in production and losses of negative ions and excited hydrogen molecules in the expansion region [12].

4. Conclusions

The study presents experimental arrangements and results from measurements of the electronegativity and the density of the negative hydrogen ions in the expansion region of a tandem plasma source. The gas pressure and the absorbed power are varied in the experiment. The results show that both the electronegativity and the density of the negative ions increase with the absorbed power increase and have a weak dependence on the pressure. An optimal pressure range – (1-5) Pa – for negative ion production in the expansion region is determined.

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