High and low electronegativity mode in cc-rf oxygen plasma

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The low pressure 13.56 MHz cc-rf oxygen plasma can operate in two different modes of electronegativity defined by $\alpha = \tilde{n}_- / \tilde{n}_e$. The high ($\alpha > 2$) and low ($\alpha < 0.1$) electronegative mode and the transition between them depends on the processing parameters rf power and total pressure. The line integrated electron and negative atomic oxygen ion density is measured by 160 GHz Gaussian beam microwave interferometry and simultaneous laser photodetachment. Consequently, the afterglow behavior in a 10 Hz (50 % duty cycle) pulsed rf plasma is influenced by these two modes. For high electronegativity an electron density peak appears in the early afterglow, whereas for the low electronegative there is none. A 0d afterglow model is applied which describes well the two modes.

Introduction and Experiment

This contribution discusses the appearance of two modes of electronegativity in a 13.56 MHz cc-rf oxygen plasmas. Therefore, it is discussed the electron and negative ion density [1] in cw and pulsed rf oxygen plasma. The oxygen plasma is generated in a cylindrical stainless steel vacuum chamber with a diameter and a height of 400 mm, see scheme in figure 1. The powered stainless steel water cooled electrode has a diameter of 100 mm. The electrode shielding and the chamber wall are grounded which provides a strongly asymmetric rf discharge. The rf power was varied between 10 to 100 W, which corresponds to a self-bias of -50 to -600 V. Two big windows (fused silica) with a diameter of 140 mm are used for undisturbed passing the Gaussian microwave beam through the vacuum chamber. The 160.28 GHz microwave interferometer is used for line integrated electron density measurement. This high frequency permits on the one hand the description of the microwave free space propagation by Gaussian beam propagation theory and ensures on the other hand a sufficient spatial resolution of 10 mm in the discharge centre. The temporal resolution amounts to of about 200 ns. This is high enough to measure fast electron density changes, required for the photodetachment of negative ions. The photodetachment technique bases on the measurement of electrons being released from the negative atomic oxygen ion by a short laser pulse. Therefore, it is merged a Nd:YAG laser working at the second harmonics ($\lambda = 532$ nm) with the microwave beam. The measured density of the released electrons provides information about the negative ion density.

High and low electronegativity ($\alpha = \tilde{n}_- / \tilde{n}_e$) mode and their characteristics

The measured line integrated electron density ($\tilde{n}_e$) is between 10^{14} and $10^{16}\,\mathrm{m}^{-2}$ and the negative ion density ($\tilde{n}_-$) between 2×10^{14} and $10^{15}\,\mathrm{m}^{-2}$. For both species a jump in the density can be observed for rf power of about 50 W, see figure 2. Hence, the plasma operates at high electronegativity mode with $\alpha > 2$ for low rf power and at low electronegativity mode with $\alpha < 0.1$ for high rf power. Furthermore, the electron relaxation time after the laser pulse is of about 1 µs for $\alpha > 2$ and is much shorter than for $\alpha < 0.1$ with relaxation times of about 100 µs. This mode transition is discussed in detail in [1]. In the case of high electronegativity the electron density relaxation can be described by a simple 0D-attachment-detachment model. This model provides an estimation about the density of the metastable molecular oxygen density. Furthermore, the effective attachment rate coefficients for $O_2\left(X^3\Sigma_g^-\right)$ and $O_2\left(a^1\Delta_g\right)$ were determined using the model in combination with measured electron and negative ion density as well the electron relaxation time constant. They are in comparable order of magnitude as the

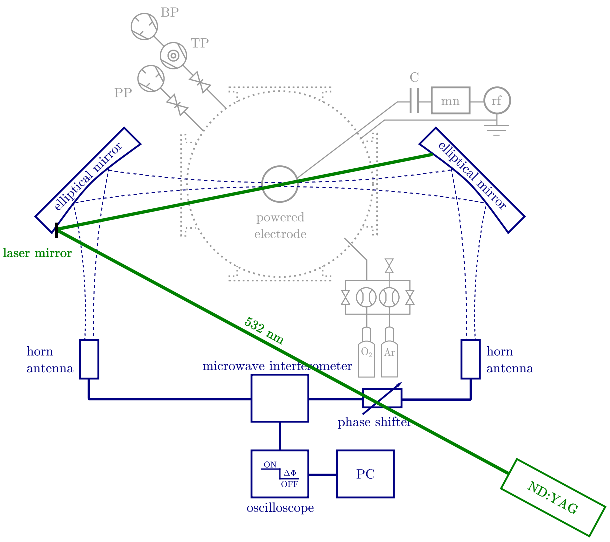

Fig. 1: Schematic top view picture of the discharge setup with the 160 GHz interferometer and the laser beam guidance of the Nd:YAG laser for photodetachment.

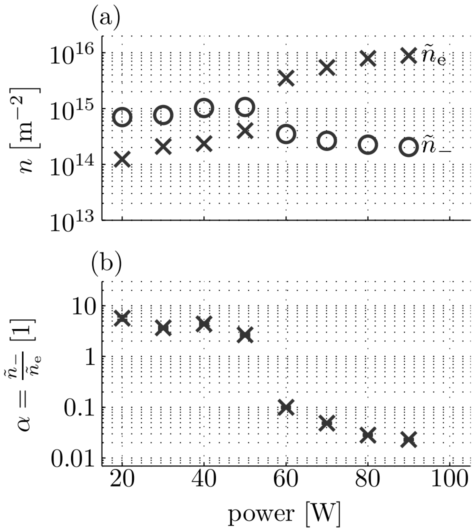

Fig. 2: (a) Mean on phase line integrated electron $\tilde{n}_e$ ($\times$) and negative ion density $\tilde{n}_-$ ($\circ$) over rf power variation at 30 Pa and 5 sccm. (b) Is the electronegativity $\tilde{n}_-/\tilde{n}_e$.

literature values, [2, 3]. Thereby, the model reveals the significant influence of the metastable molecular oxygen $O_2\left(a^1\Delta_g\right)$ on attachment and detachment processes.

Furthermore, the electronegativity influences the afterglow behavior for a 10 Hz pulsed oxygen plasma (50 % duty cycle). For the low electronegativity case the electron density immediately decreases after disabling the rf power. This is the same behavior it was observed for an electropositive argon plasma [4]. Whereas, for the high electronegativity mode (low rf power) it was measured an electron density increase in the early afterglow up to few 100 µs after disabling the rf power for a wide pressure range from 20 to 100 Pa. As mentioned above the negative ion density is comparable or even higher than the electron density in this mode. Therefore, the first assumption is that the detachment of negative ions in the afterglow can produce electrons. Whereby, on the one hand it is important that electrons are produced via detachment processes in the afterglow. But on the other hand it is also important that these electrons are not more able to produce negative ions by dissociative attachment. Thats because the attachment rate coefficients strongly depends on the electron temperature. The electron temperature quickly decreases in the afterglow over orders of magnitude within a time lower than 1 µs [5]. To proof our assumptions it was applied a 0D model for the afterglow phase. It is considering particle balance equations for six species (O_2^+, O_2^-, O^-, e, $O_2(a^1\Delta_g)$, O) and eight elementary reactions. The measured steady state density of negative ions and electrons in the plasma-on phase of the pulsed rf plasma as well as plausible assumptions concerning the density of atomic oxygen and metastables are taken into account as initial conditions. This rate equation system was numerically solved. The model fits very well the measured temporal behavior of the electron density. Not alone the electron peak for high electronegativity mode can be reproduced. Also the low electronegativity mode with the immediately decrease of the electron density after disabling the rf power can be described by the model. A main conclusion from the model is that the $O_2(a^1\Delta_g)$ are the dominant species for detachment of the negative oxygen ions and therewith the main electron production channel in the afterglow.

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