Electrode floating voltage measurements for determination of ion density in pulsed dusty plasmas

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I Introduction

Usual methods for measuring ion densities in low temperature plasmas, such as Langmuir probes, can be inaccurate in measurements of dusty and reactive plasmas. Due to the thin film deposition on the probe or plasma perturbations in the vicinity of the probe, the real ion density in reactive plasmas can be underestimated. Experimental results show that the ion density in reactive plasmas can be determined by using a non invasive method of electrode floating voltage analysis. A very good agreement between ion density and electron density is observed, which will be presented in this paper.

II Experimental setup

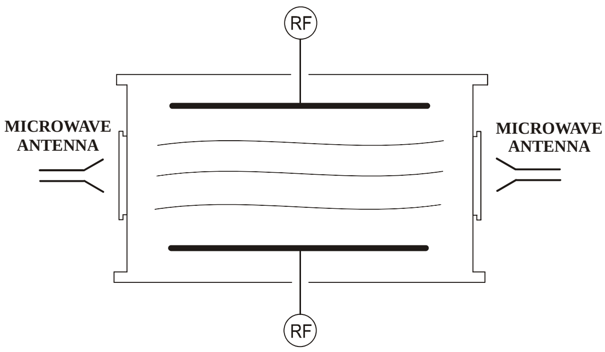

Fig. 1 Experimental setup

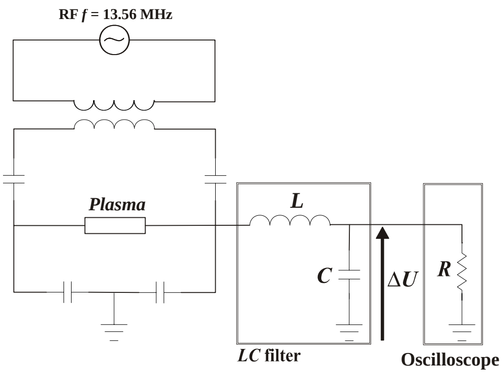

Fig.2 The equivalent electrical circuit
L = 400 μH, C = 0.47 μF, R = 1 MΩ

Measurements of ion densities were performed in low-pressure capacitively coupled discharges, symmetrically driven by RF frequency at 13.56 MHz (Fig.1). The discharge was produced between 2 parallel-plane stainless steel electrodes with 30 cm in diameter and 7 cm distance between them. The signal from the RF generator was square-wave modulated and it varied between 100 Hz and 1 kHz with 50% duty cycle. The RF input power ranged between 10 W and 80 W. The gas pressure was kept constant at 0.1 mbar for flow rate of 8 and 0.5

sccm for argon and acetylene, respectively. For a single RF power, different mixtures were examined: pure argon plasma (Ar), argon/acetylene plasma before the dust formation (Ar/C_2H_2) and pure argon plasma with levitating dust particles inside, obtained by stopping the acetylene flow (Ar/dust). The hydro-carbonaceous nano-particles were produced in a line-averaged process of reactive plasma polymerization of acetylene monomer. Electron densities were measured by the means of super-heterodyne microwave interferometer, with working frequency 26.5 GHz and time resolution of 1 μs. The details of experimental setup can be found elsewhere [1].

III Measurements and results

The basis for the proposed method for ion density measurement is the analysis of the floating voltage of each electrode. In the equivalent electrical circuit (Fig.2) plasma is treated as a non-linear element. Each electrode is coupled with a capacitor C through a large inductance L (LC circuit). The electrode voltage is superposition of RF signal and DC bias voltage, which appears as the result of either geometrical or electrical asymmetry in the chamber. The LC circuit behaves like a high-frequency filter for the RF signal, passing only the low frequency of 100 Hz. Consequently, the output voltage measured on capacitance C follows slowly the changing floating voltage of the electrode.

In the afterglow of 100 Hz square-modulated plasma, experimental data (Fig.3) show that the time constants for discharging the capacitor C is around 1 ms for different powers, which is in contrast to the theoretical value, corresponding to the discharging through the input impedance of the oscilloscope *2RC*, approx. 1 s. One order of magnitude difference brings to the conclusion that the capacitor C is discharging mostly through the afterglow plasma. The fitted discharge time constants correspond to the discharge time constants of plasma.

In the model for indirect measurement of ion density, the plasma is treated as a capacitor which discharges by collecting positive ions in the plasma afterglow. During the plasma afterglow, the floating voltage of the electrode remains negative (Fig.4), repelling the electrons and collecting the positive ions. The total number of collected ions N_{ions} is obtained from the change of voltage ΔU on the capacitance C of the LC filter in the plasma afterglow. The ion density is estimated by dividing the total number of collected ions by active plasma volume V:

$$N_{ion} = C\Delta U/e \;\Rightarrow\; n_i = N_{ion}/V$$

The ion densities in this model were calculated with the assumption that there were no other significant losses of the ions, such as recombination in the plasma or on the dust particle.

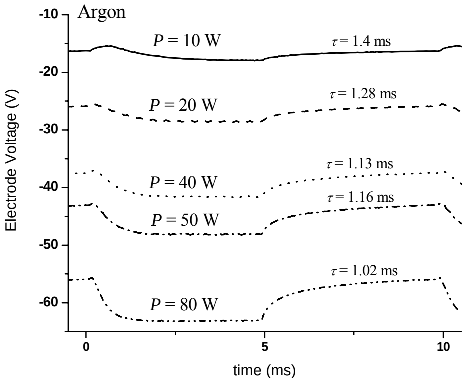

Fig.3. Time behaviour of floating electrode voltage in pure argon plasma for different powers. Fitted capacitor discharging constants are shown for the plasma afterglow. Pulsing frequency is 100 Hz and duty cycle 50 %.

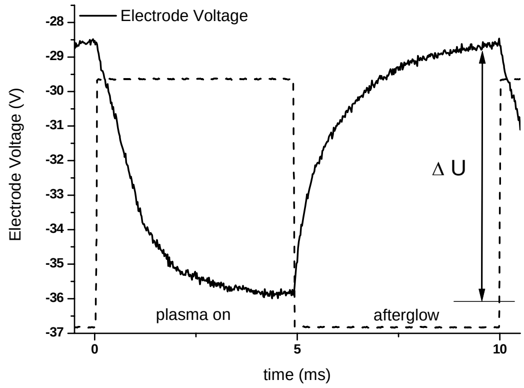

Fig.4. Electrode floating voltage in the plasma afterglow remains negative (solid line). Dashed line depicts plasma pulsing at 100 Hz and 50 % duty cycle.

Figure 5 displays experimental results for ion and electron densities for different applied powers in dust-free and dusty plasmas. The ion densities were calculated using the described method, while electron densities were measured independently by the microwave interferometer. Electron density may be slightly overestimated due to the line of sight averaging process, not taking into account plasma protruding outside the electrode region. A good agreement between ion and electron densities can be seen for pure argon and argon/acetylene plasma (Fig. 5(a)), keeping the condition of quasi-neutrality sustained: $n_i \approx n_e$. It can be concluded that the main loss channel of ions in a dust free discharge is ambipolar diffusion to the electrodes.

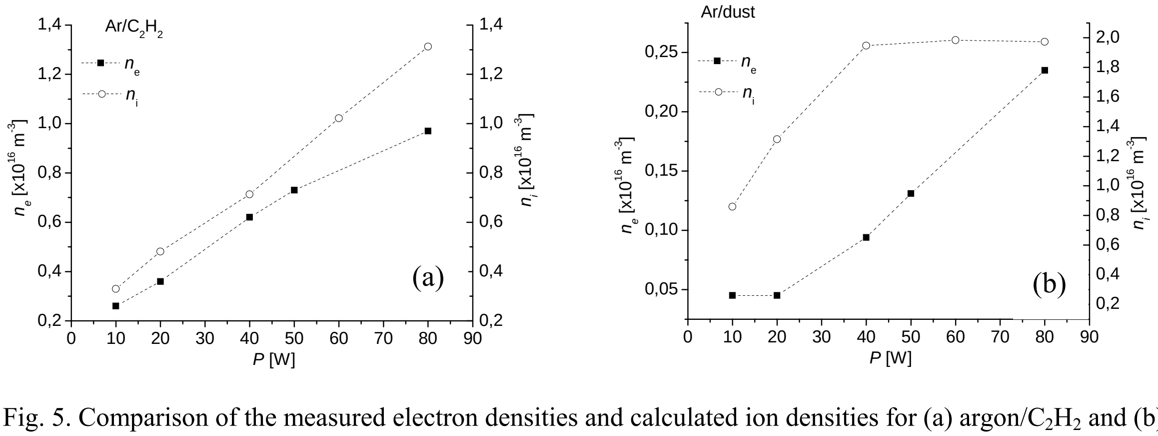

Fig. 5. Comparison of the measured electron densities and calculated ion densities for (a) argon/C_2H_2 and (b) argon/dust plasma for different RF powers

In dusty plasmas, the presence of dust particles strongly influences the electron density. As expected, electron density is decreased compared to the dust-free case, due to formation of negatively charged dust particles, which collect free electrons (Fig.5(b)). Consequently, the quasi-neutrality condition has to include dust particle charge in dusty plasmas $n_i \approx n_e + n_d|Z_d|$, where n_i, n_e and n_d are ion, electron and dust densities respectively and Z_d is the number of electrons per dust particle. The presence of dust in plasma opens a new channel for losses – dust particles behave like floating probes emerged in plasma and electrons and ions are colliding with them, recombining on their surface and forming neutral atoms or molecules. Increase of free-electron temperature is compensating the additional losses, leading to higher excitation and ionization rates. Consequently, the metastable and ion densities are higher in dusty plasmas, as shown in [2], which is also observed by applying the proposed method.

Comparison between losses to the dust particles and to the walls is necessary for the estimation of ion density. A spatially-averaged theoretical model for an argon plasma afterglow with nano-sized dust particles is being developed, in which the time dependences of different plasma parameters have been calculated. The balance equation for the ions

$$\frac{\partial n_i}{\partial t} \approx -n_i/\tau_{iw} - K_d^i n_i n_d + k_m n_m^2$$

includes (RHS) the terms for ion losses to the walls, to the dust particles and ion generation in metastable pooling process, respectively. First calculations show that in the dusty plasmas nearly the same amount of ions is recombined on the dust particles as diffuses to the walls.

IV Conclusions

The proposed model for measuring ion densities in the reactive plasmas showed good agreement in case of Ar and Ar/C_2H_2 plasma before the formation of the dust particles. In the dusty plasmas, the presence of dust opens a new loss channel for the ions, which is shown to be of approximately the same magnitude as the ion diffusion to the walls. Further investigations of ion densities determined by the proposed method include the influence on the loss rate of the ions by changing the electrode distance and the influence on the ion diffusion constant with different pressures.

V Acknowledgements

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