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Charged species dynamics in capacitively coupled radio-frequency plasmas

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Capacitively coupled radio frequency (CCRF) discharges have widely been employed in semiconductor industry. An in-depth understanding of the fundamental process, e.g., charged species dynamics, in CCRF plasmas can improve the performance of plasmas sources used in practical processing.

In electropositive CCRF plasmas, e.g., in an Ar plasma, the RF voltage between the two electrodes drops primarily across the sheath regions, while the electric field strength in the bulk plasma is quite weak. The electrons gain energy primarily by interacting with the oscillating sheath edges (α-mode). However, at very low pressure, when the driving frequency and electrode gap satisfy a certain resonant condition, a substantial amount of electrons can bounce back and forth between two sheath edges, and can be "coherently" heated. This is the so-called "bounce resonance heating", which can significantly enhance the ionization and excitation rates, and, consequently, the plasma density.

By increasing the working pressure and/or the RF voltage, the CCRF discharge can transition from the α-mode into γ-mode, in which secondary electrons emitted from the electrodes due to ion bombardment cause most of the ionization/excitation inside the sheath region. In this regime, the plasma density increases much faster than linearly with the RF voltage.

In both α and γ modes, the electron power absorption, as well as the ionization rates are typically high around the sheath edges and low in the plasma bulk. However, in electronegative plasmas, e.g., CF_4 gas, electrons can also gain energy inside the bulk region. This is because in electronegative plasmas, the drift electric field in the plasma bulk and ambipolar electric field at the edge of the collapsing sheath can heat electrons, causing ionization/excitation in the bulk region (DA-mode). The transitions between α, γ and DA modes can be induced by changing external parameters.

It should be noted that in previous studies of low pressure RF plasmas the ion motion are not modulated at RF frequency (due to their heavy masses), only the mobile electrons were supposed to be able to instantaneously follow the alternating RF electric field and, thus, be accelerated to high energies, sustaining plasma. If the ion plasma frequency, however, becomes comparable to, or higher than the driving frequency, positive and negative ions may respond to the RF electric field, generating space charges. This may lead to the formation of striations.

We observed the self-organized striated structures of the plasma emission in CCRF CF_4 plasmas by Phase Resolved Optical Emission Spectroscopy and their formation was analyzed and understood by PIC/MCC simulations [1]. The striations were found to result from the periodic generation of double layers due to the modulation of the densities of positive and negative ions upon responding to the external RF electric field.

The measured spatio-temporal electronic excitation patterns at various external parameters (driving frequency, pressure, RF voltage, etc.) show a good agreement with the simulation results. In the presence of striations, the minimum (CF_3^+, F^-) ion densities in the bulk region exhibit an approximately quadratic increase with the driving frequency, while they are independent of other external parameters. With these densities, the eigenfrequency of the ion-ion plasma is near the driving frequency, indicating that a resonance occurs between the positive and negative ions and the oscillating electric field inside the plasma bulk. A discharge mode transition from the "DA" into "striated" mode can be induced by increasing the pressure or RF voltage. The distance between striations is found to decrease with the driving frequency and/or the pressure, and is almost independent of the RF voltage and the electrode gap.

References

[1] Liu Y X, et al, Experimental observation and computational analysis of striations in electronegative capacitively coupled radio-frequency plasmas, Phy. Rev. Lett. (2016) **116**, 255002

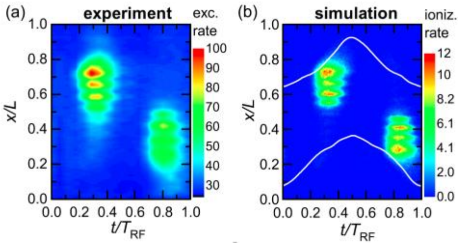

Figure 1 (a) Measured electron-impact excitation rate and (b) simulated spatiotemporal ionization rate (in units of 10^{21} $m^{-3}s^{-1}$). The powered electrode is at x/L = 0, the grounded electrode is at x/L = 1.

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