Ionization Dynamics in Capacitively Coupled Discharge Biased with Tailored Voltage Waveform: Role of Secondary Electrons

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Abstract: Capacitively coupled plasmas (CCP) are commonly used in semiconductor etching and deposition. We investigated CCPs biased with triangular waveforms using high-speed imaging and PIC/MCC simulations, highlighting the impact of secondary electron emission and how tailored waveforms improve control over ionization and electron energy distribution in low-pressure CCP discharges.

1. Introduction

The energetic electrons in capacitively coupled plasmas drive the plasma chemistry by transferring energy to neutrals through collisions [1]. In low-pressure CCPs with electropositive gases, ionization can occur at the bulk edge during sheath expansion, or it can be dominated by secondary electrons (SE) within the sheath, depending on the strength of the electric fields [2]. The voltage waveform tailoring provides enhanced control over the sheath voltages, altering the ionization dynamics of plasma by manipulating electron energy distributions (EED). [3]

In this work, we investigated the ionization dynamics of CCPs biased via triangularly-shaped tailored waveform using high-speed sheath imaging and particle-in-cell Monte Carlo collisions (PIC/MCC) simulations.

2. Methods

We simulated the capacitively coupled argon discharge at 10mTorr with a 5 cm gap between the electrodes using a one-dimensional Electrostatic Direct Implicit Particle-In-Cell (EDIPIC) code.[4] The upper electrode was driven by a 60 MHz sinusoidal waveform, and the lower electrode was biased with a 400 kHz tailored voltage waveform. The SE emission yields were varied to investigate the influence of SE on ionization within the sheath and the bulk plasma.

For high-speed imaging of the plasma sheath near the biased electrode, the ICCD camera (PI-MAX 4) was utilized to capture sheath images with a gate width of 17 ns. The images were acquired at distinct time intervals, corresponding to specific points along the tailored voltage waveform. This approach facilitated a comprehensive analysis of the temporal evolution and dynamics of the plasma sheath.

3. Results and Discussion

Figure 1 presents the time-resolved electron density and sheath movement near the biased electrode. The sheath fully expanded during the negative potential in the waveform with ionization in the sheath region. The simulation results reveal distinct sheath dynamics during different waveform cycles. Specifically, during the positive pulse, the electric field reversed direction, causing the electron flux to be directed toward the biased electrode, which resulted in an enhanced electron current at that surface. In contrast, during the negative cycle, increased ionization was observed within the sheath, driven by a dominant ion flux toward the biased electrode, where SE emission due to ion bombardment significantly contributes to local ionization. Furthermore, the energetic SEs ejected from the upper electrode may play a crucial role in sustaining ionization within the sheath and influencing the overall plasma behavior.

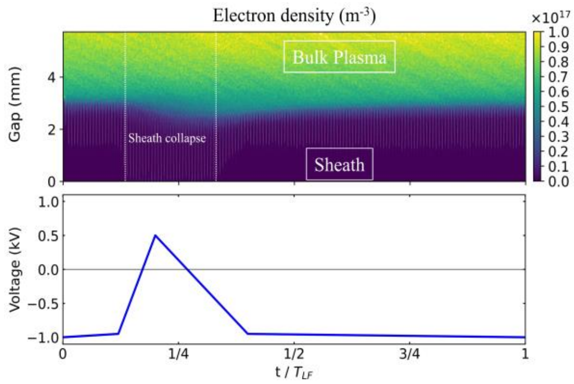

Fig. 1. The time-resolved electron density near the biased sheath and voltage at the biased electrode from PIC/MCC simulation.

4. Conclusion

The use of tailored waveform in low-pressure CCPs significantly influenced the discharge behavior. Our combined experimental and simulation results revealed that the SE play critical role in ionization in the sheath.

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