Analysis of local ion tilting in a capacitively coupled pulsed plasma using a two-dimensional particle-in-cell simulation

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Abstract: The effects of varying LF pulse voltage on the plasma density uniformity and local ion tilting in Ar capacitively coupled plasmas are analyzed with a two-dimensional particle-in-cell simulation. As the LF pulse voltage increases, the steady-state plasma density decreases significantly at the wafer center compared with the edge. It causes the slope of the equipotential line near the edge to be steeper, leading to wider incident angles of ions on the wafer.

1. Introduction

In the etching process for semiconductor manufacturing using a capacitively coupled plasma (CCP), dual-frequency (DF) driving or non-sinusoidal pulsed waveforms are commonly used to control the ion flux and the ion energy angular distribution function (IEADF). However, while a DF effectively controls the IEADF, it can lead to changes in plasma density which, in turn, affects the incident ion angles on the wafer. This occurs not only at the wafer edge but also at the center, posing a critical issue as it can directly impact product yield.

Here, we analyzed the local ion tilting at various wafer positions using a two-dimensional (2D) particle-in-cell (PIC) simulation accelerated by a graphics processing unit.

2. Simulation Conditions

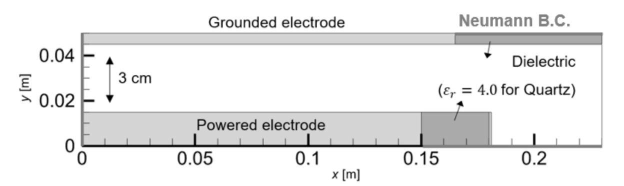

Fig. 1. Simulation domain of CCP equipment.

Figure 1 shows simulation domain used in this study. We performed simulations using a 2D PIC code parallelized with a GPU to model argon discharges. A simplified structure was used to simulate a rectangular geometry CCP reactor, where the top electrode was powered, and the bottom and sidewall electrodes were grounded. To simulate a 300 mm wafer process, the bottom electrode length was set to 15 cm. The distance between the electrode edge and the sidewall is fixed to 5 cm to minimize the sidewall effects. The DF effect was analyzed by fixing the high-frequency (HF) voltages at 3,000 V and varying the low-frequency (LF) pulse voltage from 0 to 5000 V. The driving frequencies were 60 MHz for the HF and 400 kHz for the LF. The background pressure was set to 15 mTorr, with a neutral gas temperature of 300 K. A gap distance of 3 cm was chosen for the simulation.

3. Results and Discussion

With a single-frequency (SF) driving, the electron density peaks at the center. However, as the LF pulse voltage increases, the electron density at 3,000 V becomes similar at the center and the edge. When the LF pulse voltage increases over 4,000 V, the edge density becomes higher than the center density.

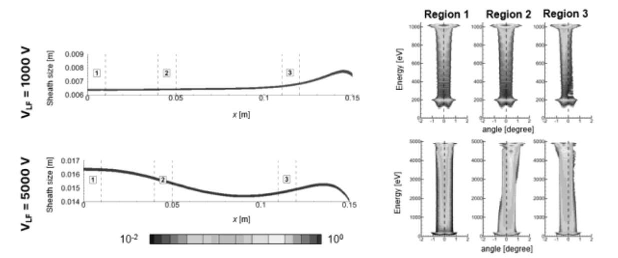

Fig. 2. The sheath size on the bottom electrode and the ion energy angle distribution function (IEADF) for region 1 (0<x<0.01 m), region 2 (0.04<x<0.05m), and region 3 (0.11<x<0.12m) for V_{LF} = 1,000 and 5,000 V.

Figure 2 shows the sheath size and IEADF at the specific region for two cases: one for the electron density having a peak at the center (V_{LF}=1,000 V), and the other having a peak at about x=0.09 m (V_{LF}=5,000 V). At the center of the wafer, most ions are incident vertically (0°), as confirmed by the IEADF measured in Region 1 for both V_{LF}=1,000 V and 5,000 V. For V_{LF}=1,000 V, most ions are also incident vertically in region 2, where the electron density is nearly uniform along the x-direction. However, for V_{LF}=5,000 V, the electron density increases in region 2, and the sheath size decreases. Thus, most ions are incident with positive angles. In region 3, where the electron density decreases, and the sheath size increases, ions are incident with negative angles in both cases.

4. Conclusion

In this study, a 2D-PIC simulation was used to investigate the effect of varying LF pulse voltages on the IEADFs toward the wafer. The electron density decreases more significantly at the center than at the edges as the V_{LF} increases, which significantly changes the spatial distribution of equipotential lines. In particular, when V_{LF} increases, the density decreases more at the center rather than the edge. This causes the slope of the equipotential line near the edge to become steeper, leading to wider incident ion angles on the wafer.