9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Parameter dependences of charged particle dynamics and electron power absorption mode in dual-frequency capacitively coupled argon discharges

Kai Zhao[1], Yang Zhou[1], and You-Nian Wang[1]
[1] School of Physics, Dalian University of Technology
e-mail (speaker): kaizhao@dlut.edu.cn

Dual-frequency capacitively coupled plasma sources having a low-frequency blow 1 MHz have received growing attention for their ability to finely tune plasma characteristics—especially ion energy and ion flux—supporting advanced etching processes essential for modern microelectronics fabrication. As the device feature size shrinks to an atomic scale, the processing requirements of high-aspect-ratio (HAR) etching become more stringent. More energetic positive ions are required to penetrate deeply into the etched trenches to avoid unwanted etching profiles affected by notching, trenching, and twisting.[1] Under specific discharge conditions, lowering the low-frequency (LF) can produce increased ion energy with a narrower angular spread, which is crucial for achieving high selectivity, anisotropy, and critical dimension control required for HAR etching.[2-3]

We have investigated the plasma density and ion energy/angular distribution dependencies on the LF (f_L) in a low-pressure (2 Pa) DF CCP by combining experiments and kinetic particle simulations. As f_L decreases from 6.8 MHz to 40 kHz, the plasma density undergoes a moderate decline initially, followed by an increase, reaching a maximum at 400 kHz (see Figure 1). The improved plasma density is attributed to a combined effect of (i) attenuation of the modulation effect of the LF source on the high-frequency electron heating and (ii) enhanced emission of electron-induced secondary electrons. In addition, a lower f_L can yield a higher ion energy with a narrower angular spread. Both features favor the HAR etching extensively used in the semiconductor industry.

The dependences of the charged particle dynamics and electron power absorption mode on the low-frequency (LF) voltage amplitude (V_L), high-frequency (HF) voltage amplitude (V_H), and gas pressure (p) in 400 kHz/27.2 MHz DF capacitively coupled argon discharges have also been investigated by experimental diagnostics and particle-in-cell/Monte Carlo collision simulations. Compared to a single-frequency 27.2 MHz discharge, the addition of the LF source is found to significantly affect the electron-impact excitation/ionization dynamics via frequency coupling and secondary electron emission. At p = 40 Pa and V_H = 225 V, both n_e and $I_{750,ave}$ experience a moderate decline followed by a dramatic rise with the increase of V_L, corresponding to an electron power absorption transition from α-mode to a hybrid α-γ-mode. The decline in n_e and $I_{750,ave}$ versus V_L at V_L < 300 V is caused by a reduced bulk electron power deposition and a stronger frequency coupling effect at a higher V_L. For a constant V_L, both n_e and $I_{750,ave}$ decline monotonically with decreasing V_H, which is due to a weakened HF electron heating, a reduced bulk electron power deposition, and a stronger frequency coupling effect at a lower V_H. With the decrease of V_H, the electron power absorption switches from α-mode to the hybrid α-γ-mode at a higher V_L. n_e and $I_{750,ave}$ exhibit distinct dependences on V_L at different p. For a constant V_L, both n_e and $I_{750,ave}$ decrease monotonically with p. With decreasing p, the electron-impact mean free path increases so that the γ-electrons accelerated by the sheath electric field can traverse a long distance across the bulk region or even incident on the opposite electrode without any collisions with neutral particles. Consequently, at a high V_L, the electron power absorption switches from the hybrid α-γ-mode to an almost pure α-mode with the decrease of p. This work has been financially supported by the National Natural Science Foundation of China (NSFC) (Grants No. 12005035, and No. 11935005), and the Fundamental Research Funds for the Central Universities [Grant No. DUT23RC(3)059].

References

[1] F. Krüger *et al*, Plasma Sources Sci. Technol. **28**, 075017 (2019).
[2] Y. Zhang *et al*, J. Vac. Sci. Technol., A **31**, 061311 (2013).
[3] S. Huang *et al*, Plasma Sources Sci. Technol. **24**, 015003 (2014).

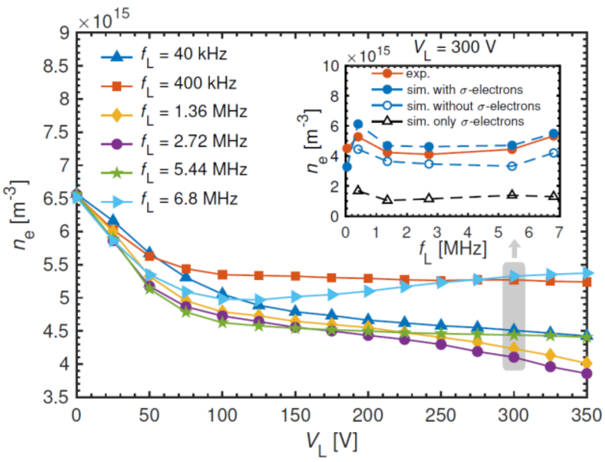

Figure 1. Experimentally determined plasma density n_e at the discharge center vs LF voltage amplitude V_L (0 V ≤ V_L ≤ 350 V) in DF argon discharges at six typical values of f_L. Other discharge conditions: p = 2 Pa, V_H = 120 V, and f_H = 27:2 MHz. The inset illustrates the variation of n_e vs f_L at V_L = 300 V and V_H = 120 V, obtained by experiments (solid red circles) and simulations with (solid blue circles) and without (hollow blue circles) γ-electrons taken into account.