Investigation of Transient Phenomena of Electron Heating in Low-Frequency Pulse-Driven Capacitively Coupled Ar Plasmas Using a Particle-in-Cell Simulation

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Pulsed capacitive RF plasma is demanded for the semiconductor etching because it mitigates plasma-induced damage. Repeating pulse-on and pulse-off time lowers ion energy and electron temperature compared to a continuous wave plasma, resulting in less wafer damage. This study performed a pulse-driven two-dimensional (2D) particle-in-cell (PIC) simulation parallelized with a graphics processing unit (GPU) to investigate the plasma dynamics for the time duration of ms. We investigated the effects of a 2D electrode structure empowered low-frequency (LF) pulsed voltage added to a high-frequency (HF) sinusoidal wave on the plasma potential, electron density, and electron temperature by varying frequency and pressure conditions. Plasmas diffuse for a sufficiently long afterglow period in the LF pulse and re-ignited from a lower electron density when the pulse is on again. The electron heating mechanisms are reported for the ramp-up and ramp-down phases at different frequencies.

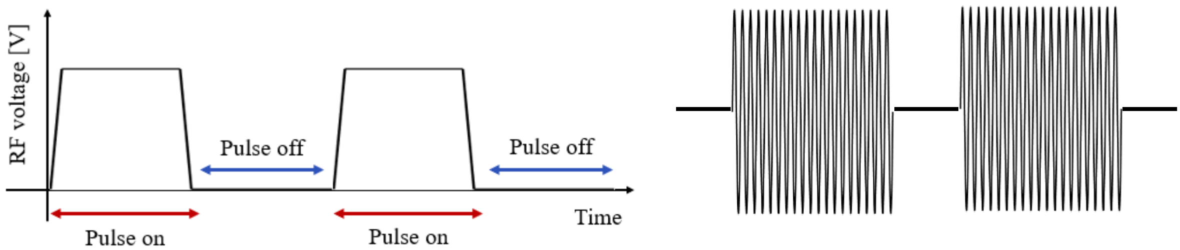

Fig. 1. The shape of the applied pulse envelope and the voltage waveform

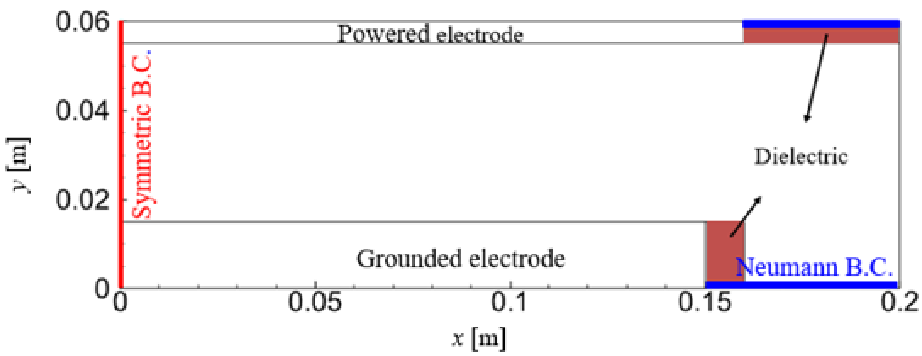

Fig. 2. The simulation domain

Simulation condition	
Time step	10 ps
Gas Type	Argon
High Frequency	40 MHz
LF Voltage(enveloped)	1000 V
Duty ratio	20 %
Gap distance	0.04 m
Dielectric (ε_r)	4.0

Case No.	Gas pressure [mTorr]	Low Frequency [kHz]
1	20	400
2	20	40
3	20	4
4	7.5	400
5	100	400

Table 1. Simulation parameters

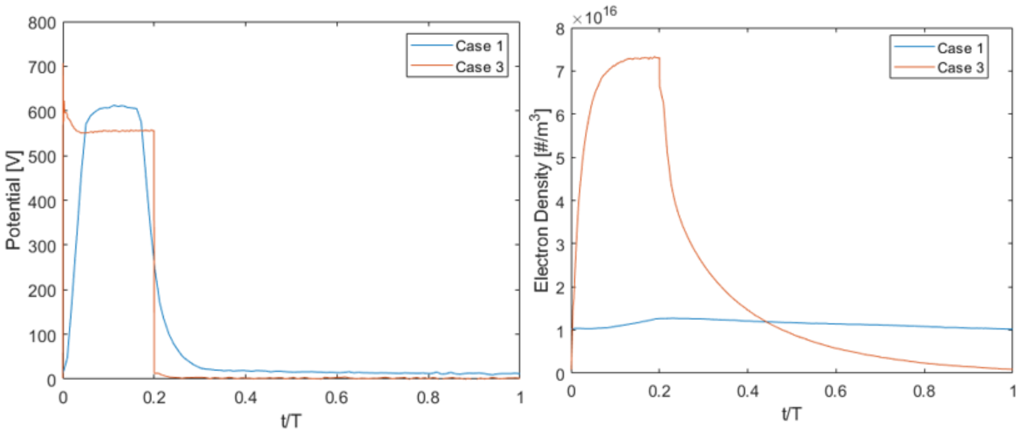

Fig. 3. The time-evolution of the plasma potential and electron density for Cases 1 and 3. The electron density changes abruptly over time for 4 kHz drive but not for 40 or 400 kHz.

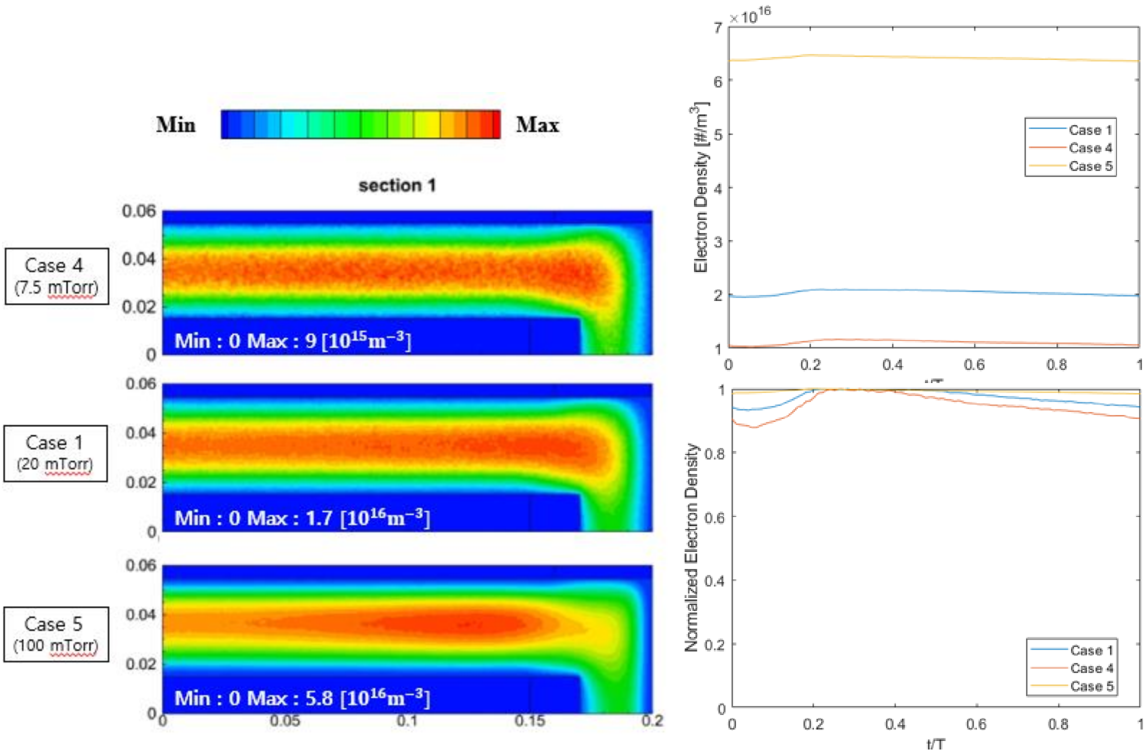

Fig. 4. Electron density profiles (LHS) and the time evolution of the electron density at the center (RHS) for Cases 1, 4, and 6. The electron density at the center rarely changes over time at high pressure.

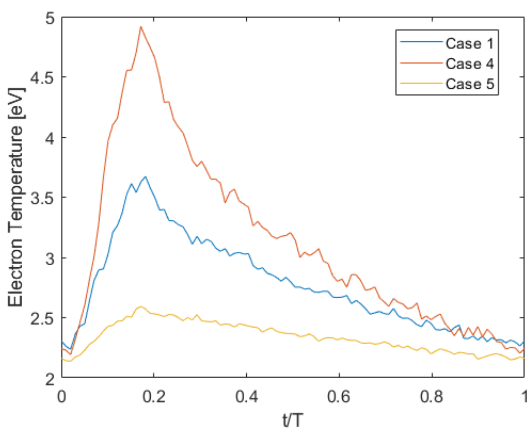

Fig. 5. The time evolution of the electron temperature at the center for the variation of gas pressure of 7.5, 20, and 100 mTorr.