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Impedance matching of pulse modulated capacitively coupled plasmas

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With the scaling of semiconductor processes toward atomic dimensions and increasing structural complexity of transistors, optimizing plasma sources has become increasingly challenging. Pulsed Capacitively Coupled Plasma (Pulsed-CCP) has garnered significant attention for its flexible control and reduced wafer damage, making it a promising approach for advanced process applications. [1,2] Due to the strong nonlinearity of the plasma in Pulsed-CCP sources and the non-stable characteristics of pulse power modulation, impedance matching between the plasma load and RF power supply becomes extremely challenging.

In order to solve the above problems, firstly a self-consistent method for coupling the external circuit with the plasma kinetic model is proposed. [3] Based on this, an analytical iteration-based approach for matching continuous wave plasma was investigated. [4] Since the impedance of the plasma is almost constant after the discharge reaches steady state, it is not surprising that a high quality match is achieved. Since the impedance changes rapidly during pulse modulation, traditional mechanical-based capacitance adjustment is difficult to respond in time, so the method based on driving frequency tuning is considered to have potential. Recent simulation work has demonstrated the effectiveness of frequency modulation for improving matching quality. [5]

In this work, a typical pulsed single-frequency capacitively coupled discharge is set up and simulated. The plasma is described by a kinetic Particle in Cell simulation complemented by Monte Carlo treatment of collisions (PIC/MCC). An external circuit containing an L-type matching network and a stray branch is described by differential equations, and coupled to the plasma model based on [3]. When the circuit components are fixed at the optimal settings under continuous wave discharge operation, the simulation results show that the impedance of the plasma changes rapidly within the initial few tens of μs when the pulse is turned on and off, thus causing drastic changes in the reflection, as shown in Figure 1. Although relatively good matching quality is also occurring in the late stage of the pulse on phase as the density reaches a steady state, this does not happen often, especially when the pulse repetition frequency is high and the duty cycle is small. Here, it is assumed that the adjustment of the variable capacitor is delay-free, and the time variation of the optimal capacitance values required within the pulse period can be calculated based on the impedance curve of the CCP. By using these time-varying capacitor values, the matching quality is significantly improved. Then, the effect of capacitor adjustment delay on matching is investigated.

References

[1] Banna, Samer, et al. "Pulsed high-density plasmas for advanced dry etching processes." *Journal of Vacuum Science & Technology A* 30.4 (2012).
[2] Economou, Demetre J. "Pulsed plasma etching for semiconductor manufacturing." *Journal of Physics D: Applied Physics* 47.30 (2014): 303001.
[3] Yu, Shimin, et al. "A generalized external circuit model for electrostatic particle-in-cell simulations." *Computer Physics Communications* 282 (2023): 108468.
[4] Yu, Shimin, et al. "Best impedance matching seeking of single-frequency capacitively coupled plasmas by numerical simulations." *Journal of Applied Physics* 132.8 (2022).
[5] Yu, Shimin, et al. "Impedance matching assistance based on frequency modulation for capacitively coupled plasmas." *Journal of Applied Physics* 137.3 (2025).

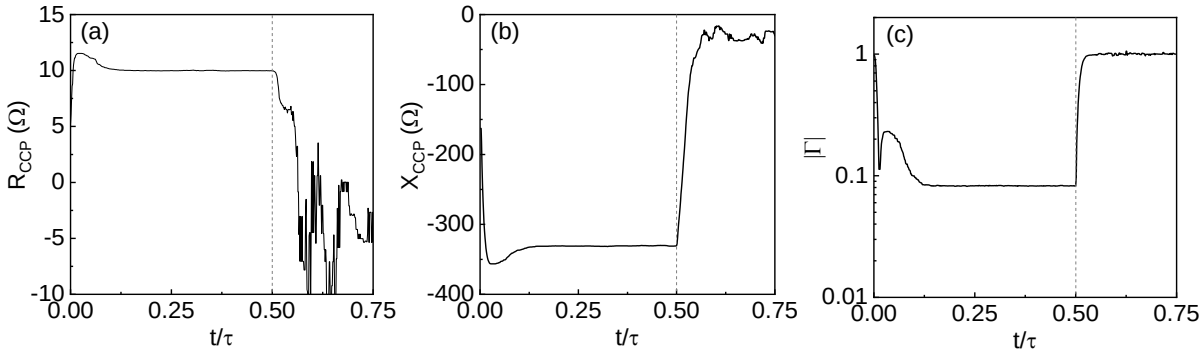

Figure 1. Electrical parameters during a pulse modulated CCP discharge. (a) Resistance of the plasma; (b) Reactance of the plasma; (c) Amplitude of the impedance reflection coefficient at the input of the impedance matching network. τ is the pulse repetition period (590μs). The RF of the generator is 13.56 MHz. The pulse repetition frequency and duty cycle are 1.695 kHz and 50 % respectively. The background gas is pure argon and at 200 mTorr.