Effect of Blocking Capacitance on RF Voltage Coupling in a 40 MHz Capacitively Coupled Plasma

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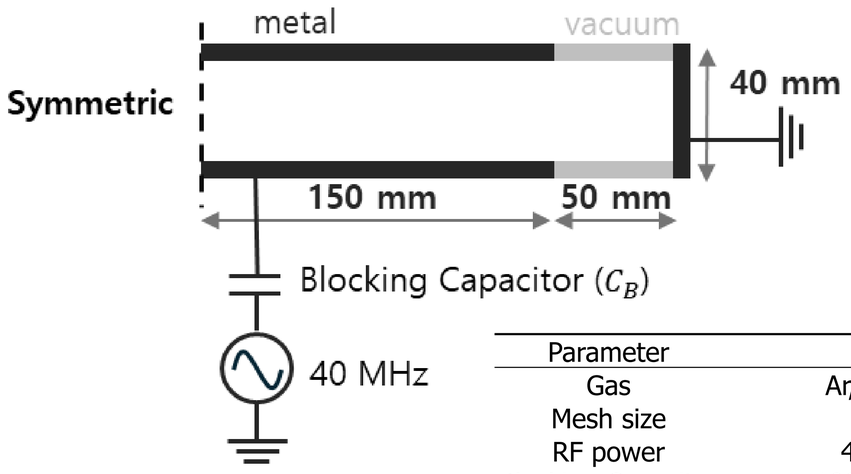
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Introduction

- Capacitively coupled plasmas (CCPs) are widely used in semiconductor processing, where RF-driven sheath dynamics play a critical role in electron heating and ion bombardment.
- A blocking capacitor connected in series with the powered electrode enables DC self-bias formation. However, its finite reactance can also influence RF voltage coupling to the plasma [1,2].
- This study investigates the effect of blocking capacitance (100 pF, 1 nF, and 10 nF) on the electrical response and plasma characteristics of a 40 MHz argon CCP using EDIPIC-2D PIC/MCC simulations.

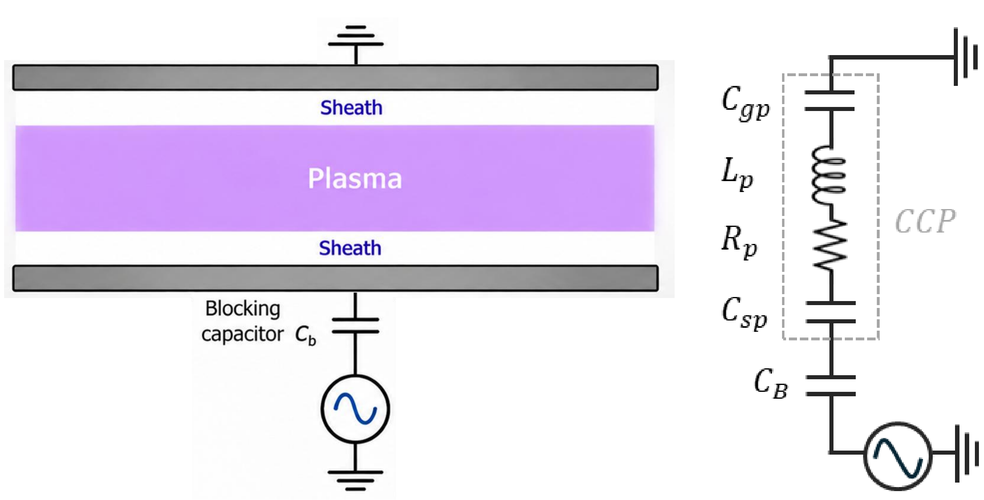
Simulation Setup

<Chamber configuration for PIC simulation>



Parameter	Input
Gas	Ar, 20 mT, 300 K
Mesh size	0.1 mm
RF power	40 MHz, 500V
Blocking Capacitor	100 pF, 1 nF, 10nF

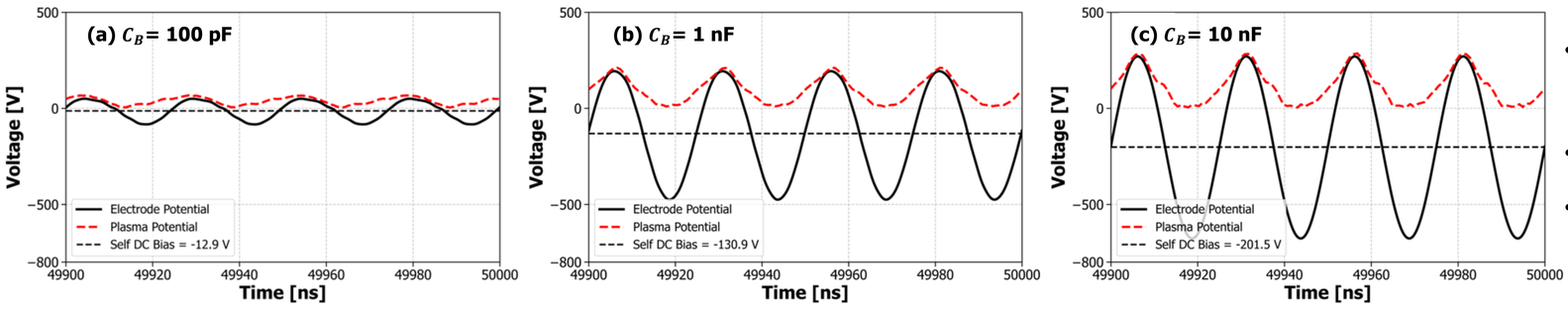
<Equivalent Circuit Model of CCP>



- A two-dimensional PIC/MCC simulation was performed using EDIPIC-2D, with an asymmetric CCP geometry consisting of a 150 mm metal-electrode region, a 50 mm vacuum region, and a 40 mm gap [3].
- Argon plasma was simulated at 20 mTorr and 300 K, with a spatial grid size of 0.1 mm. A 40 MHz sinusoidal RF voltage with a peak amplitude of 500 V was applied to the powered electrode through a blocking capacitor (100 pF, 1 nF, or 10 nF).
- Each simulation was performed for 50 μs, and the final 40 RF cycles were analyzed to evaluate the electrode and plasma potentials, RF voltage coupling, and electrical impedance characteristics.

Results and Discussion

☐ Powered-electrode and plasma potentials



- At a fixed source voltage of V_s=500 V, reducing C_B from 10 nF to 100 pF decreases the electrode-voltage swing from 947.8 V to 133.0 V
- The DC self-bias shifts from −201.5 V to −12.9 V.
- The plasma-potential modulation is also reduced, indicating weaker RF voltage coupling to the discharge.

☐ Fundamental circuit analysis

Quantity	100 pF	1 nF	10 nF
$\lvert V_{e,pp}\rvert\ [V]$	133.0	669.2	947.8
$Z_{CCP,1}\ [\Omega]$	1.34−j5.89	0.595−j8.30	0.570−j7.43
$\angle Z_{CCP,1}\ [^o]$	-77.2	-85.9	-85.6
$C_{CCP,1}\ [pF]$	676	479	536
$C_{CCP,app}\ [pF]$	656	477	531
$\lvert H_1\rvert$	0.1322	0.6772	0.9496
$P_1\ [W]$	80.3	491	1151
$n_{e,max}\ [m^{-3}]$	3.49 × 10^{15}	1.26 × 10^{16}	2.41 × 10^{16}

- The two sheaths are predominantly capacitive, $Z_{sp} \approx 1/(j\omega C_{sp})$ and $Z_{sg} \approx 1/(j\omega C_{sg})$. Bulk electron–neutral momentum loss and electron inertia are represented by R_P and $j\omega \mathrm{L_p}$. Total impedance of the CCP system becomes, $Z_{CCP} = Z_{sp} + (R_p + j\omega L_p) + Z_{sg}$.
- The fundamental impedance, $Z_{CCP,1} = V_{e,1}/I_1$, was calculated from the 40 MHz electrode-voltage and total external-current phasors extracted by harmonic fitting over the final 40 RF cycles.
- The measured voltage transfer magnitude, $|H_1| = \mathrm{V_{e,1}/V_{s,1}}$, decreased from 0.9496 at 10 nF to 0.6772 at 1 nF and 0.1322 at 100 pF, indicating that the regime changes from the CCP-load-dominated regime to the blocking-capacitor-dominated regime.
- The effective series capacitance, $C_{CCP,1} = -1/\omega\ Im(Z_{CCP,1})$, characterizes the net capacitive reactance of the CCP. It agrees within approximately 3% with the capacitive-divider estimate, $H_1 \approx |Z_{CCP,1}|/(|Z_{CCP,1}| + |Z_{B,1}|) \approx C_B/(C_B + C_{CCP})$.
- All cases remain predominantly capacitive. At 100 pF, however, the impedance phase shifts to −77.2° and the real part increases to 1.34 Ω, indicating a greater departure from purely capacitive behavior.
- The fundamental real power delivered to the CCP, $P_1 = \frac{1}{2} Re(V_{e,1} I_1^*)$, decreased from 1151 W at 10 nF to 80.3 W at 100 pF, accompanied by a lower maximum electron density.

Conclusion

- The CCP impedance became increasingly capacitive as the blocking capacitance increased, with the impedance phase approaching −90° at 1 nF and 10 nF. At 100 pF, the non-capacitive contribution was more pronounced.
- As the blocking capacitance decreased from 10 nF to 100 pF, the fundamental real power delivered to the CCP decreased from 1151 W to 80.3 W, accompanied by a reduction in maximum electron density from 2.41 × 10^{16} to 3.49 × 10^{15} m^{-3}.
- These results demonstrate that blocking capacitance significantly influences RF voltage coupling and therefore the electrical response and excitation of the plasma.

Future Work

- Investigate a wider range of blocking capacitances and RF frequencies to characterize the transition between CCP-load-dominated and blocking-capacitor-dominated coupling regimes.
- Apply low frequency bias voltage to evaluate the effect of blocking capacitance on the ion energy distribution.
- Evaluate the convergence of DC self-bias and its influence on ion energy distributions at the powered electrode under different blocking capacitances.

Acknowledgement

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Reference

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- [2] P. Chabert and N. Braithwaite, Physics of Radio-Frequency Plasmas, Cambridge University Press, 2011.
- [3] Princeton University, EDIPIC-2D, open-source repository, accessed Aug. 2026.