

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

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1. Introduction

Capacitively coupled plasmas (CCPs) are widely used in semiconductor processing because of their simple geometry and their ability to control ion bombardment through the electrode sheaths. A conventional CCP consists of two parallel electrodes, with one driven by a radio-frequency (RF) source and the other grounded. The applied RF voltage produces time-varying sheath fields that transfer energy to electrons and sustain the discharge through electron-impact ionization.

In addition, a blocking capacitor is commonly connected in series with the powered electrode. Its primary functions are to interrupt the DC current path and to provide charge storage, thereby allowing a DC self-bias to develop in response to the asymmetric current balance at the plasma sheaths [1,2]. In conventional CCP operation, the blocking capacitance is generally selected to be sufficiently large that its reactance at the driving frequency is small compared with the impedance of the discharge. Consequently, its influence on RF voltage coupling is often neglected. However, the blocking capacitor remains a reactive element connected in series with the CCP load. As the blocking capacitance decreases, its reactance increases and may become comparable to or even larger than the effective impedance of the CCP. Under such conditions, a fraction of the applied RF voltage can drop across the blocking capacitor rather than across the plasma, thereby reducing the RF voltage coupled to the discharge.

This study investigates the effect of blocking capacitance on a 40 MHz argon CCP using the two-dimensional EDIPIC-2D particle-in-cell/Monte Carlo collision (PIC/MCC) code [3]. Three capacitances, 10 nF, 1 nF, and 100 pF, are compared in terms of powered-electrode potential, plasma potential, dc self-bias, and electron density. The simulated voltage division is then interpreted using an equivalent circuit model to estimate the effective CCP capacitance and to assess the transition from CCP-load-dominated to blocking-capacitor-dominated voltage coupling.

2. Methods

2.1 PIC/MCC simulation setup

The computational geometry is shown in Fig. 1(a). The domain was symmetric about its centerline, with a

150 mm long metal-electrode section and an additional 50 mm long vacuum section at the outer boundary on each side. The electrode gap was 40 mm. Argon at 20 mTorr and 300 K was simulated using a spatial grid size of 0.1 mm. A 40 MHz sinusoidal voltage source with a peak amplitude of 500 V was connected to the bottom electrode through C_B . Each simulation was performed for 50 μ s and the final 40 RF cycles were analyzed.

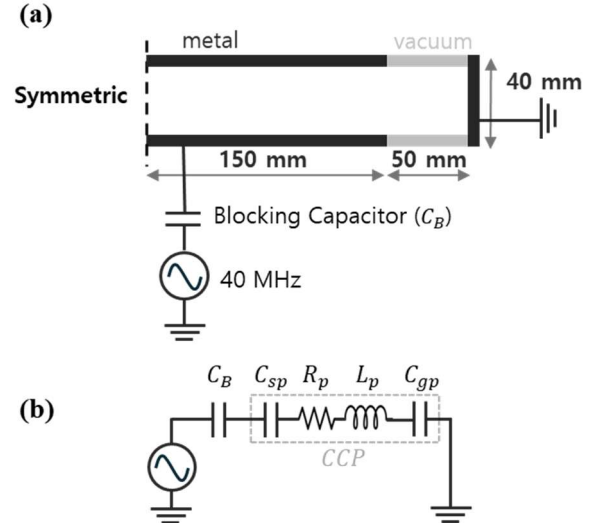


Fig. 1. (a) EDIPIC-2D computational domain and external circuit, and (b) equivalent circuit of the blocking capacitor and CCP load.

2.2 Equivalent circuit model

Figure 1(b) represents the source, blocking capacitor, powered sheath, quasi-neutral bulk, and grounded sheath as a series network. Electron depletion in a sheath separates electrode charge from positive space charge; a time-varying sheath voltage therefore changes the stored charge and produces displacement current. At the fundamental frequency, the two sheaths are consequently predominantly capacitive, with $Z_{sp} \approx 1/(j\omega C_{sp})$ and $Z_{sg} \approx 1/(j\omega C_{sg})$ [1,2]. In the bulk, electron-neutral momentum loss converts electrical energy into heat and is represented by R_p , whereas finite electron inertia delays the RF current response and produces the inductive term $j\omega L_p$.

$$Z_{CCP} = Z_{sp} + (R_p + j\omega L_p) + Z_{sg} \quad (1)$$

Only when $|Z_{bulk}| \ll |Z_{sp} + Z_{sg}|$ may the bulk be neglected and the two sheaths be replaced by a single

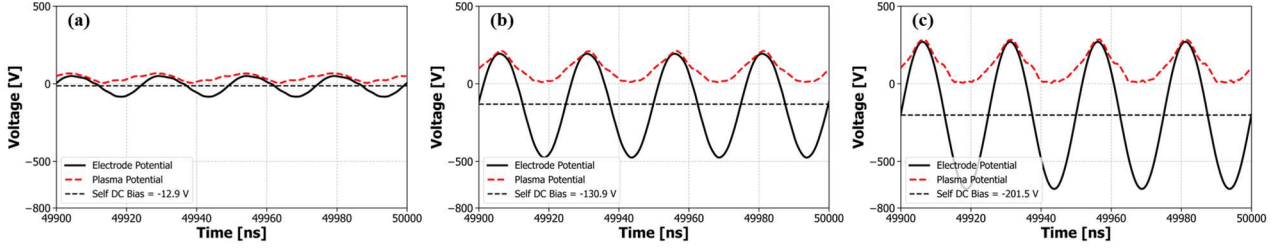


Fig. 2. Powered-electrode and plasma potentials for $C_B =$ (a) 100 pF, (b) 1 nF, and (c) 10 nF for the last four RF cycles.

series capacitance. The present analysis retains the complete complex impedance.

2.3 Fundamental impedance and sheath analysis

The applied source voltage $V_s(t)$, the electrode voltage $V_e(t)$, and the total external current $I(t)$ were obtained from the circuit history over the last 40 RF cycles. These quantities define the electrical response of the CCP as viewed from the external circuit. Each waveform was represented by a dc component, an optional linear drift, and the first three harmonic components using a least-squares harmonic fit.

$$x(t) = x_0 + a t + \text{Re} \left\{ \sum_{k=1}^3 X_k e^{jk\omega t} \right\} \quad (2)$$

Only the first-harmonic coefficient was used for the fundamental impedance analysis. Because the grounded electrode was maintained at $V_g = 0$, $V_e(t)$ represents the voltage across the complete CCP load, including the powered sheath, bulk plasma, and grounded sheath. The direct 40 MHz fundamental CCP impedance was then obtained from,

$$Z_{CCP,1} = V_{e,1}/I_1. \quad (3)$$

The transfer factor was evaluated as,

$$H = \frac{V_{e,1}}{V_{s,1}} \quad (4)$$

3. Results and Discussion

Figure 2 shows that reducing C_B attenuates both the electrode voltage and the plasma potential modulation. The peak-to-peak voltage, $V_{e,pp}$, decreased from 947.8 V at 10 nF to 669.2 V at 1 nF and 133.0 V at 100 pF, while the dc self-bias changed from -201.5 to -130.9 and -12.9 V. The source voltage was maintained at approximately $V_{s,pp} = 1000$ V. Thus, only a small fraction of the applied RF voltage reached the CCP when the blocking capacitance was 100 pF, whereas nearly the entire source voltage was applied to the CCP at 10 nF.

At 40 MHz, the magnitude of the blocking-capacitor impedance decreased from 39.79 Ω at 100 pF to 3.98 Ω at 1 nF and 0.398 Ω at 10 nF. The fundamental CCP impedances evaluated directly from Eq. (3) were 0.570-j7.43 Ω , 0.595-j8.30 Ω , 1.34-j5.89 Ω for 10 nF, 1 nF, and 100 pF cases, respectively. The effective CCP capacitances inferred from the imaginary part of the fundamental CCP impedances,

$$C_{CCP,1} = -\frac{1}{\omega \text{Im}(Z_{CCP,1})} \quad (5)$$

are then 536 pF, 479 pF and 676 pF respectively.

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

Table 1. Quantities obtained from the EDIPIC-2D simulation and fundamental circuit analysis.

The measured voltage transfer magnitude, $|H_1|$, from Eq. (4) 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.

When both the blocking capacitor and the CCP load are approximated as capacitive elements, the voltage-transfer magnitude can be expressed as,

$$H_1 \approx \frac{|Z_{CCP,1}|}{|Z_{CCP,1}| + |Z_{B,1}|} \approx \frac{C_B}{C_B + C_{CCP}}. \quad (6)$$

Then the apparent C_{CCP} can be evaluated as,

$$C_{CCP,app} = C_B \frac{1-H}{H} \quad (7)$$

and the relative errors between $C_{CCP,1}$ and $C_{CCP,app}$ are 0.98 %, 0.49 %, and 2.89 % for 10 nF, 1 nF, and 100 pF respectively. This close agreement indicates that the fundamental CCP response remains predominantly capacitive in all cases. The higher relative error for 100 pF case resulted from the increased non-capacitive contribution as shown in the increased real part of the impedance. This result may indicate that the decreased plasma density, identified by the bulk electron density, increased the resistance and inductance at the bulk plasma.

At 100 pF, approximately 86.8% of the source-voltage amplitude appeared across the blocking capacitor, while only 13.2% was transferred to the CCP. At 1 nF, the CCP fraction increased to 67.7%, and at 10 nF, it reached 94.9%. Therefore, increasing C_B shifts the voltage distribution continuously from the external capacitor toward the plasma load.

This voltage partition should not be interpreted as a partition of dissipated power. An ideal blocking

capacitor does not absorb cycle-averaged real power. Instead, its reactance controls the RF current and the voltage available across the dissipative part of the CCP impedance. The fundamental real power delivered to the CCP is described as follows.

$$P_1 = \frac{1}{2} \text{Re}(V_{e,1} I_1^*) \quad (8)$$

The fundamental real power delivered to the CCP decreased from 1151 W at 10 nF to 491 W at 1 nF and 80.3 W at 100 pF. Consistently, the maximum electron density decreased from $2.41 \times 10^{16} \text{ m}^{-3}$ at 10 nF to $3.49 \times 10^{15} \text{ m}^{-3}$ at 100 pF.

4. Conclusion

The effect of blocking capacitance on RF coupling in a 40 MHz argon CCP was investigated using EDIPIC-2D. The fundamental voltage-transfer magnitude decreased from 0.9496 to 0.6772 and 0.1322, corresponding to CCP-load-dominated, transition, and blocking-capacitor-dominated regime, respectively. The fundamental real power delivered to the CCP decreased from 1.15 kW at 10 nF to 491 W at 1 nF and 80.3 W at 100 pF, accompanied by a reduction in the maximum electron density from $2.41 \times 10^{16} \text{ m}^{-3}$ at 10 nF to $3.49 \times 10^{15} \text{ m}^{-3}$ at 100 pF. The CCP response remained predominantly capacitive over the investigated range, although a larger non-capacitive contribution appeared at 100 pF. These results show that a small blocking capacitor suppresses plasma excitation when the impedance becomes non-negligible compared to the impedance of the chamber itself.

Acknowledgments

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