Discharge asymmetry induced by the pulsed radio-frequency current

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Through particle-in-cell/Monte Carlo simulations, the discharge asymmetry induced by the pulsed radio-frequency (rf) form of the driving current is found in capacitively coupled plasmas. It is shown that this discharge asymmetry originates from the phase shift between the rf current and voltage during the current-on time. Consequently, the degree of the asymmetry can be controlled by varying the phase of the rf current. As the duty ratio decreases, the plasma density decreases but the dc bias increases. Hence, it is possible to control the ion flux and ion bombardment energy independently by varying both the amplitude of the rf current and the duty ratio. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1646458]

Capacitively coupled radio-frequency (rf) discharges have been extensively studied for the last decades because of their interesting physics as well as their widespread applications.[1,2] Most capacitive discharges are asymmetric. This asymmetry plays an important role to determine the ion bombardment energy at the powered electrode which is one of the critical parameters in the plasma processing. There have been a few studies on the discharge asymmetry which comes from the geometric asymmetry—the time-averaged plasma density is shifted to the electrode with the larger area (commonly, grounded electrode).[3,4] However, since the electrodes are usually positioned inside the chamber, it is not easy to control the asymmetry flexibly by varying the ratio of two electrode areas. On the other hand, conventional capacitive reactors have some drawbacks, such as the lack of the independent controllability of the ion flux and ion bombardment energy. Hence, they have been continuously modified for further improvements of their performance. For example, the pulsed plasmas have attracted much attention.[5–9] However, most of these works on pulsed plasmas have been limited only for the discharge driven by the pulsed form of the voltage rather than the current.

In this letter, we report on the discharge asymmetry which is induced by the pulsed rf form of the driving current in the capacitively coupled plasma (CCP). For this study, we have used a one-dimensional electrostatic particle-in-cell (PIC) simulation with a Monte Carlo collision (MCC)[10–12] which is a self-consistent and fully kinetic method. Our simulations were performed for an argon discharge with the symmetric configuration of the gap length of 4 cm and operating at the gas pressure of 20 mTorr. The current source was applied to the powered electrode at position $x=0$ cm. The electric potential at this boundary is found by applying Kirchhoff's current law.[12] The electrode at position $x=4$ cm was grounded. The secondary-electron emission coefficient for argon ions was set to 0.2 while electrons were assumed to be perfectly absorbed at electrodes. In order to obtain the meaningful result of the steady state, we ran the simulations for several thousand rf cycles.

The shape of the driving current is the periodic repetition of the current-on time and the current-off time as follows:

$$J(t)=\begin{cases}\sin(2\pi f_{\mathrm{rf}}t+\phi) & 0\leqslant t<\alpha\tau\\ 0 & \alpha\tau\leqslant t<\tau\end{cases}. \tag{1}$$

During the on time, the rf current of frequency f_{rf} (=13.56 MHz) and phase ϕ is applied with the amplitude of 1 mA/cm^2, and during the off time, the current is fixed to 0 mA/cm^2. The duty ratio α ($0<\alpha\leqslant 1$) is the ratio of the on time to one period. The conventional rf discharge corresponds to the $\alpha=1$ case. The pulse period τ was fixed to ten times an rf period ($\tau=10\tau_{\mathrm{rf}}$). For simplicity, we restricted $\alpha\tau$ to the integer times an rf period in our simulations. It is noted that the applied current is symmetric since the time-averaged value of Eq. (1) over the pulse period is zero.

Figures 1(a) and 1(b) show the spatial profiles of the ion density and potential for various duty ratios with the zero rf phase. They were averaged over several pulse periods. The discharge is symmetric when the conventional shape of the current is applied ($\alpha=1$). However, in the pulsed discharge ($\alpha<1$), the ion density is shifted to the right-hand side. (RHS) so that the discharge is not symmetric. The time-averaged sheath voltage on the left-hand side (LHS) is also larger than that on the RHS because of the negative dc bias on the powered electrode. In order to investigate the nature of the asymmetry, the time evolution of the voltage on the powered electrode in the pulsed discharge was compared with the conventional case. Figure 1(c) shows the time evolutions of the voltage and current on the powered electrode for the duty ratio of 0.5 with the zero rf phase. It was shown for one pulse period in the steady state. Even when the current is zero at the beginning of the off time, the voltage has a nonzero negative value due to the phase difference of around $\pi/2$ between the current and voltage. During off time, the absolute value of this voltage decreases. However, it does not decay rapidly since the ion transit time to the sheath[13] (a few μs) is slow compared with the off time (less than μs). Thus, the time-averaged voltage over the off time becomes nonzero negative. This is the mechanism that the pulsed dis-

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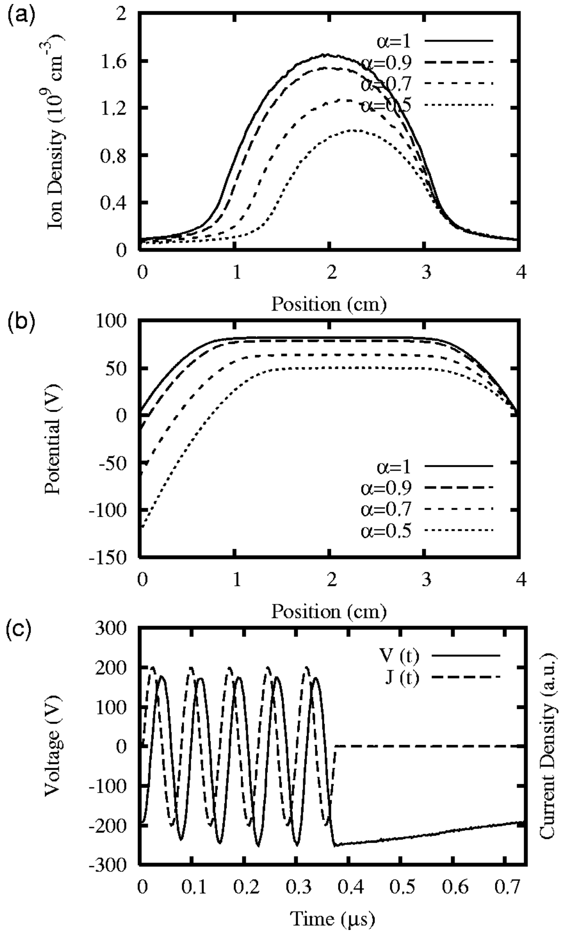

FIG. 1. The spatial profiles of (a) the ion density and (b) potential for various duty ratios. (c) The time evolutions of the voltage and current on the powered electrode for the duty ratio of 0.5.

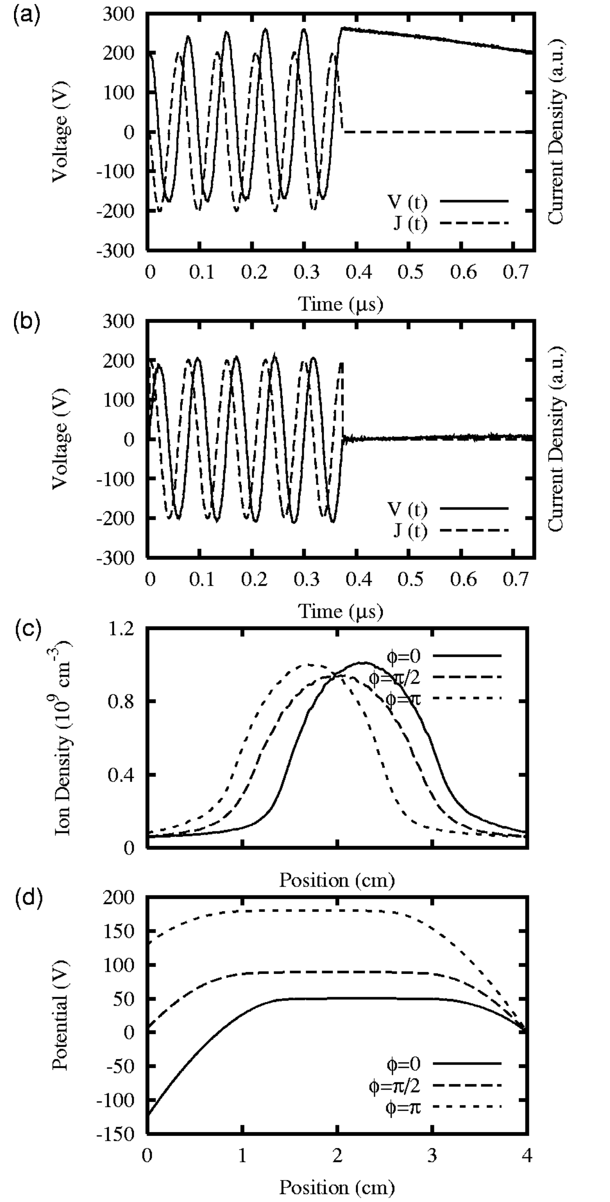

FIG. 2. The time evolutions of the voltage and current on the powered electrode for the rf phases of (a) π and (b) $\pi/2$. The spatial profiles of (c) the ion density and (d) potential for various rf phases.

charge becomes asymmetric in spite of the symmetry of the geometry and the current. It is also noted that there exists the asymmetry even during the on time as a consequence of the asymmetric discharge during the off time. Since it was found that the phase difference between the current and voltage plays an important role to make the discharge asymmetric in the pulsed discharge, we have also simulated for the different rf phases of the current.

The time evolutions of the voltage and current on the powered electrode were compared for various rf phases with the fixed duty ratio of 0.5. For the rf phase of π, the voltage is positive at the beginning of the off time as shown in Fig. 2(a). Hence the time-averaged voltage over a pulse period is positive. For the rf phase of $\pi/2$, the voltage becomes zero at the beginning of the off time as shown in Fig. 2(b). The spatial profiles of the ion density and potential are shown in Figs. 2(c) and 2(d) for various rf phases. For the rf phase of $\pi/2$ which is close to the phase difference between the current and voltage, the discharge is symmetric and the dc bias on the powered electrode is zero. When the rf phase is zero, the plasma density is shifted to the RHS and the dc bias is negative. This result has been achieved in the conventional discharge where the powered electrode has a smaller area than the grounded one. When the rf phase is π, the plasma density is shifted to the LHS and the dc bias is even positive. This result has been obtained in the conventional discharge where the powered electrode has a larger area than the grounded one. Thus, the rf phase in the pulsed discharge can be used to control the asymmetry as the ratio of two electrode areas has been used in the conventional discharge. In addition, we formulated approximately the output voltage obtained by the PIC–MCC simulations. It was found that the dc bias derived from the formulated voltage is proportional to $(1-\alpha)\sin(\phi+\phi_J)$ where ϕ_J is the phase of the voltage with respect to the current. This analytic result is consistent with our PIC–MCC simulations.

The ion peak density and voltages are shown as a function of the duty ratio in Figs. 3(a) and 3(b) which were obtained from the spatial profiles in Figs. 1(a) and 1(b). The plasma density and, hence, the ion flux decrease linearly with the decrease of the duty ratio. In low-pressure rf discharge, the ion bombardment energy is determined by the time-averaged sheath voltage which is the difference between the plasma potential and the dc bias on the electrode. As shown in Fig. 3(b), for the decrease of the duty ratio, the sheath

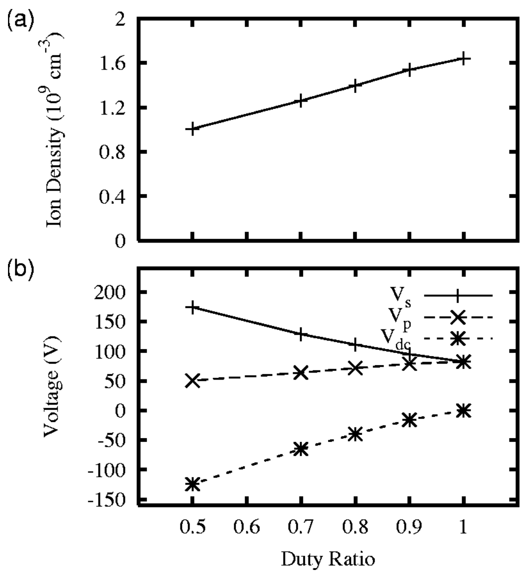

FIG. 3. (a) The ion peak density and (b) voltages as a function of the duty ratio. V_p, V_{dc}, and V_s represent the plasma potential, dc bias, and the time-averaged sheath voltage, respectively.

voltage and, hence, the ion bombardment energy increase primarily because of the increase of the dc bias. On the other hand, both the ion flux and ion bombardment energy increase with the amplitude of the rf current during the on time. Thus, it is possible to control the ion flux and the ion bombardment energy independently by varying the amplitude of the rf current and the duty ratio. We also obtained the electron power, ion power, and total power deposited into the discharge as a function of the duty ratio (not shown here). The electron power decreases with the decrease of the duty ratio because of the decrease of the plasma density. The ion power increases because of the increase of the sheath voltage. Accordingly, as the duty ratio decreases, the total discharge power is nearly constant but the ratio of ion acceleration power to electron heating power increases significantly.

In conclusion, through the PIC–MCC simulations of CCP driven with the pulsed rf current, we have found the discharge asymmetry which is induced by the pulsed rf form of the driving current. It was shown that this asymmetry originates from the phase shift between the rf current and voltage during the current-on time. Thus, in the pulsed rf current-driven discharge, the degree of the asymmetry can be controlled by varying the phase of the rf current instead of changing the ratio of two electrode areas. It is also a great advantage that the ion flux and ion bombardment energy can be controlled independently by varying both the amplitude of the rf current and the duty ratio. As the duty ratio decreases, the plasma density and the electron heating power decrease but the dc bias and the ion acceleration power increase. Since this asymmetry is not inherent from a particle phenomenon, the similar asymmetric trend might still be observed in the current-driven fluid model. It may not be easy to directly control the current in a real system. However, even for a system where it is difficult to directly apply the current, our concept can be realized by applying the voltage form which is the output of our current-driven simulation result.

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