Modeling of Perpendicularly Driven Dual-Frequency Capacitively Coupled Plasma

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We proposed an altered configuration for dual-frequency (DF) capacitively coupled plasmas (CCP). In this configuration, two pairs of electrodes are arranged oppositely, and the discharging is perpendicularly driven by two rf sources. With Particle-in-cell/Monte Carlo method, we have demonstrated this configuration can remove the harmful electromagnetic and DF coupling effects in conventional DF-CCP.

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Dual-frequency (DF) capacitively coupled plasmas (CCP) are commonly used as etching and deposition devices in the microelectronics, flat panel display and solar cells industries.\(^1\),\(^2\). Compare to the other two sources, inductive coupled plasma (ICP) and electron cyclotron resonance (ECR) discharges, CCP can produce uniform plasma over larger areas. In typical DF-CCP\(^3\),\(^4\), the two rf source with different frequencies are applied to the same electrode or the opposite two electrodes. The high frequencies (hf) source controls the plasma density while the low frequency (lf) source controls the ion flux and ion energy and angular distribution (IEDs and IADs). Quasi-independent control of plasma density and IEDFs is the main merit of DF-CCP over single-frequency CCP. Therefore DF-CCP has been widely used in state-of-art industry reactors. To achieve more flexibilities, some variants of DF-CCP, such as adopting very high frequency (VHF)\(^5\), applying additional dc source\(^6\) and series resonance CCP\(^7\), have received intense investigation recently.

High etching rates, uniformity, anisotropy, selectivity and low dielectric damage are the essential requirements of the CCP etching devices. There is no perfect solutions to satisfy all the requirements above simultaneously, one must make tradeoffs. Although successful in practice, DF-CCP still expose some problems. The first one is the electromagnetic (EM) effect\(^8\),\(^9\),\(^10\), which will occur when very high frequency (VHF) sources (typically > 60MHz) are used, and therefore the excitation wavelength \(\lambda\) is comparable to the reactor radius. Due to the standing wave effect\(^11\), the merit of plasma uniformities over large areas will be broken. The second one is hf-lf source coupling effects\(^12\). When only increasing the hf voltage, the density increases and the sheath thickness decreases, thus more ions will appear in the high energy end of IEDs. This is also not desired because of the reduced etching rate. Some configurations, like shaped electrodes\(^13\) and asymmetrical discharges\(^14\), are proposed to mitigate above harmful effects.

In this letter, we propose an altered configuration for DF-CCP. Not like the conventions disk-like cylindrical configuration\(^1\), here the discharge chamber is a three-dimensional (3D) flat regular hexahedron, whose cross-sectional schematic is shown in Fig. 1. Two pairs of rectangular electrodes are arranged oppositely, in the left/right surface and the top/bottom surface, respectively. In the front/back surface (not shown in the figure) and in the gaps between the electrode, thick dielectric insulators are placed to confine the plasmas. The discharging is perpendicularly driven by two rf sources. The smaller pairs (left and right) electrodes (LE and RE) are powered by the same hf sources, but with the phase difference of \(\pi\). This can be realized with a opposite phase power divider, for example, a balun\(^15\) applied between the rf source and the devices. The bottom electrode (BE) is powered by the lf source and the top electrode (TE) is grounded. The wafer is placed on the BE. We will demonstrate that this configuration can remove above problems.

In order to study such a configuration, we have adopted direct implicit Particle-in-cell/Monte Carlo (PIC/MC) algorithms\(^16\) in 2D planar geometry. Although this
configuration is inherently 3D, due to the confinement by the insulators, the plasma is uniform between the side-wall insulators and thus 2D model is sufficient, if the front/back spacing is large. The details of the algorithms are described elsewhere, therefore we will only present the simulation parameters here. The BE and TE lengths are $X = 8\text{cm}$, and the LE and RE lengths are $Y = 1.5\text{cm}$, therefore we have the four gaps of $0.25\text{cm}$. The hf sources of $\omega_{hf} = 60\text{MHz}$ and $V_{hf} = 50\text{V}$ or $100\text{V}$ are applied to the LE and RE, with the phase difference of $\pi$. The lf sources of $\omega_{lf} = 2\text{MHz}$ and $V_{lf} = 50\text{V}$ or $100\text{V}$ are applied to BE. In the gaps, the instant potentials are linearly interpolated. Argon gas is used with the pressure of $10\text{mTorr}$ and temperature of $300\text{K}$. We consider elastic, excitation and ionization collisions for electrons and elastic and charge transfer collisions for $\text{Ar}^+$ ions, respectively. Square cells are used, thus $X$ direction is uniformly divided to $256$ cells and $Y$ direction divided to $64$ cells. The space and time steps are fixed to all simulations, $\Delta x = 0.02/64\text{cm}$, $\Delta t = \Delta t_i = 0.5 \times 10^{-10}\text{s}$. All results are given by averaging over one lf period after reaching equilibrium of $1000$ rf periods. Because the diodes areas are equal for $X / Y$ separately and only the ideal voltage sources in the external circuit, we did not consider the external circuit and the self-biasing for simplicity.

The average potential, electron and ion density for the case of $V_{hf} = 100\text{V}$ and $V_{lf} = 50\text{V}$ are shown in Fig. 2. Near each electrode, there is a sheath, therefore the densities are in an elliptical profile and the maximum value is in the center. The sheathes are symmetric in both directions, but the average sheath thicknesses are larger for TE and BE than that for LE and RE. This is a natural result, since when the density is fixed, the sheath thickness inversely scales with the frequency.

We plotted the cross-sectional profiles of $n_e$ for different voltages in Fig. 3. The plasma density is mainly determined by the hf source. When increasing the $V_{hf}$ by two times, the electron densities also increase by a factor of larger than $2$. While when increasing $V_{lf}$, the electron densities are nearly unchanged. The cross-sectional profiles are flat in the center. As we have mentioned, in conventional DF-CCP, when increasing the hf voltage, the bulk plasma length will decrease and thus the density will decrease. In this present configuration, there is no such an effect, since the sheath thicknesses are decoupled.

The ion flux to BE is presented in Fig. 4. Similar to the density, the flux is mainly determined by the hf source. When increasing the $V_{hf}$ by two times, the flux also increase by a factor of larger than $2$. While $V_{lf}$ has no significant effects on the flux. Compare the conventional CCP driven by $13.56\text{MHz}$ source, the flux is much larger even the density value is close. In industry etching and deposition devices, it is critical to make the ion flux to the electrode be uniform over larger areas. As can be seen, over large distance (about $6\text{cm}$), the ion flux is uniform. In VHF CCP, due to the finite wave lengths effect as we have mentioned, the plasma density and ion flux will not be uniform over the wafer. In this configuration, the wafer can be placed on $X$ plate while the hf sources are in $Y$ direction, therefore the harmful EM effects are naturally removed.

In industry devices, it is also highly desired that the ions are anisotropic. The ion angle distributions (IADs) for different voltages are depicted in Fig. 5. Whatever the rf voltage is, most ions has the angle of several degrees. This means the ions still keep anisotropic in this configuration.

The last issue in this configuration is IEDs. The IEDs is influenced not only by rf frequency and voltage, but also by the ion transit time $\tau_i$. In conventional DF-CCP, if one increases $V_{hf}$ while keeping the $V_{lf}$ constant, the plasma density will increases and the sheath thickness will decrease. Therefore $\tau_i$ will decreases and the profiles
If source and the high peak are produced by the hf source. For we still have $\omega_{rf} > \omega_i$, the center energy of IEDs $V_i$...
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