# Hybrid simulation of dual-frequency biased inductively coupled $Cl_2$ plasma

L. Tong[1], Y. R. Zhang[1], D. Q. Wen[2] , Y. H. Song[1] and Y. N. Wang[1]

[1] *Key Laboratory of Materials Modification by Laser, Ion, and Electrons Beams (Ministry of Education), School of Physics, Dalian University of Technology, Dalian 116024, People's Republic of China*
[2] *Michigan State University, East Lansing, Mi 48824, USA*

**Abstract:** In this work, a hybrid model consisting of a global model combined bi-directionally with a fluid sheath model is employed to investigate the dual-frequency (DF) bias effect on the inductively coupled $Cl_2$ plasmas under different pressures. The results indicate that the DC self-bias voltage is approximately a linear function of the phase shift between the fundamental frequency and its second harmonic. By adjusting the phase shift in the range from 0 to 2π, the mean ion energy can be well modulated, while the ion flux almost remains constant.

**Keywords:** EAE, ICPs, DC self-bias voltage, mean ion energy and ion fluxes.

## 1. Introduction

Radio-frequency (RF) inductively coupled plasmas (ICPs), which are generally characterized by high plasma density due to the more effective electron heating by the inductive power, are commonly used in many nanofabrication applications in the semiconductor industry, such as material etching, thin film depositions and sputtering [1-2]. An idea of capacitive/inductive hybrid discharge is proposed, in which the plasma density and ion bombarding energy are controlled independently by the ICP power and capacitive bias power, respectively. However, during the past few years, it is very difficult to achieve ideal independent modulation of the ion flux and ion energy in biased ICP discharges, due to the strong coupling effect between the inductive power and capacitive bias power [3-5].

Actually, the coupling effect has also been observed in traditional dual frequency capacitively coupled plasmas (CCPs). Therefore, the electrically asymmetric discharge, which is driven by a funcdamental frequency and its second harmonic, has been proposed to ideally realized the separate control of the ion flux and ion energy on the substrate. Indeed, tailored voltage waveform has already showed its potential for the separate control of the ion energy and ion flux in CCPs both numerically and experimentally. However, the investigation of the electrically asymmetric effect (EAE) in ICPs is very limited. Although Zhang et al has already studies the EAE in inductively coupled $C_4F_8/SF_6$ plasmas and obtained similar conclusions as in CCPs [6], the effectiveness of the EAE on the independent modulation of the ion flux and ion energy in ICPs under various discharge conditions is not fully proved. Therefore, the purpose of this paper is to employ a hybrid model, i.e., a global model coupled bidirectionally with a sheath model, to investigate the EAE on the plasma density, dc self-bias, ion flux as well as mean ion energy in $Cl_2$ ICPs with DF bias sources. The results obtained in this work could help us to gain a deeper insight into the plasma characteristics of DF biased $Cl_2$ discharges, which is of utmost importance in the etching process.

## 2. Result

The bias voltage waveform used in this work is $V_{rf} = V_0[sin(2\pi f_{LF}t + \theta_1) + sin(2\pi f_{HF}t + \theta_2)]$, where $V_0 =$ 100 V is the voltage amplitude, $f_{LF} = 13.56$ MHz, $f_{HF} =$ 27.12 MHz, and $\theta_1 = 0^{\circ}$ is the low frequency phase angle. First, the effect of high frequency phase shift $\theta_2$ on the electron density is investigated under different pressures, i.e., 3, 5, 10, 30, 50 and 100 mTorr, and the ICP power is fixed at 500 W. It is clear from figure 1 that when the phase shift $\theta_2$ varies from $0^{\circ}$ to $360^{\circ}$, the electron density fluctuates within $\pm 10\%$ at 3 mTorr. As pressure increases, the modulation of the phase shift $\theta_2$ on the electron density becomes more obvious, i.e., the fluctuation is as high as about $\pm 21\%$ at 100 mTorr. Besides, when the phase shift $\theta_2$ is fixed, the electron density exhibits a slight increase as pressure varies from 3 mTorr to 5 mTorr. However, a monotonically decreasing trend is observed in the pressure range up to 100 mTorr, which can be attributed to the electronegativity.

Figure 2 presents the DC self-bias voltage as a function of the phase shift $\theta_2$ under various pressures. It is observed that the DC self-bias voltage varies almost linearly with the phase shift $\theta_2$, which is similar to that achieved by Skarphedinsson and Gudmundsson in capacitively coupled chlorine discharges [7], indicating that the EAE is realized in inductively coupled chlorine discharges. In addition, the influence of pressure on the dc self-bias is limited, except for the slightly lower absolute value at high pressure. This is because the electron density declines with pressure, giving rise to the relatively lower electron flux to the bottom electrode, and therefore, a lower DC self-bias voltage is developed to balance the electron flux and positive ion flux.

Finally, the influences of the bias voltage waveform on the separation control of the mean ion energy and ion flux are presented in figure 3. Figure 3(a) shows the mean $Cl_2^+$ energy bombarding the bottom electrode varies almost linearly with the phase shift $\theta_2$. When the phase shift increase from $0^{\circ}$ to $90^{\circ}$, the $Cl_2^+$ energy decreases rapidly from about 193 eV to about 134 eV, and then it rises by a factor of approximately 1.7 as the phase shift increases from $90^{\circ}$ to $270^{\circ}$, and the mean ion energy decreases again as the phase shift increases further to $360^{\circ}$. The evolution of the mean $Cl_2^+$ energy with the phase shift is similar for all pressure investigated, except that the mean $Cl_2^+$ energy decreases slightly at higher pressure, due to the more frequent collisions within the sheath region.

Figure 3(b) shows the influence of the phase shift $\theta_2$ on the $Cl_2^+$ flux under various pressures. It is clearly that the $Cl_2^+$ flux increases significantly with pressure, i.e., the $Cl_2^+$ flux almost doubles as pressure rises from 5 mTorr to 100 mTorr. Furthermore, the $Cl_2^+$ flux is also modulated by the phase shift $\theta_2$, i.e., the ion flux first decreases and then increases and finally it declines again as $\theta_2$ varies from 0° to 360°, which is similar to the mean ion energy. Besides, the modulation of $\theta_2$ on the ion flux becomes more obvious at higher pressure, i.e., the fluctuation is $\pm1.8\%$ at 3 mTorr, and the value increases dramatically to $\pm11.2\%$ at 100 mTorr.

## 3. Conslusion

In this paper, a hybrid model, i.e., a volume-averaged model coupled with a fluid sheath model, has been applied to investigate the plasma properties in dual-frequency biased inductively coupled $Cl_2$ dischrges under different pressures. The electron density, DC self-bias voltage, mean ion energy and ion flux have been explored as a function of bias voltage waveform and pressure.

The results indicate that EAE is realized in ICP $Cl_2$ discharges by applying a dual frequency bias source at the bottom electrode. By adjusting the phase shift between the fundamental frequency and its second harmonic, the plasma properties can be modulated. Besides, a DC self-bias voltage is developed on the biased electrode, which almost varies linearly with the phase shift, and thus the maximum ion energy can be modulated. Whereas, although the ion flux is also affected by the phase shift, the fluctuation is less obvious.


## 4. Acknowledgments

This work was supported by the National Natural Sciencs Foundation of China (NSFC) (Grant Nos. 11875101 and 11935005).


## 5. References


[1] M. A. Lieberman and A. J. Lichtenberg, Principles of Plasma Discharges and Materials Processes, 2nd ed (Wiley-Interscience, New York, 2005).

[2] T. Makabe and Z. L. Petrovic, Plasma Electronics: Applications in Microelectronic Device Fabrication (Taylor and Francis, New York, 2006)

[3] J. Schulze, E. Schungel and U. Czarnetzki, Appl. Phys. Lett. 100, 024102 (2012).

[4] H. C. Lee, M. H. Lee and C. W. Chung, Appl. Phys. Lett. 96, 071501 (2010).

[5] H. C. Lee and C. W. Chung. Appl. Phys. Lett. 101, 244104 (2012).

[6] Q. Z. Zhang and A. Bogaerts. Plasma Source Sci. Technol. 27, 105019 (2018)

[7] G. A. Skarphedinsson and J. T. Gudmundsson. Plasma Source Sci. Technol. 29, 084004 (2020)


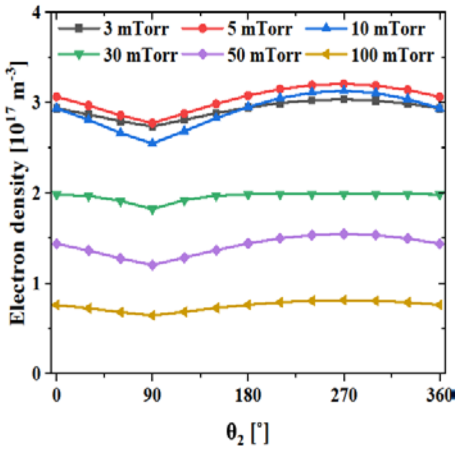


Fig. 1. Evolution of the electron density with phase shift at different pressures.

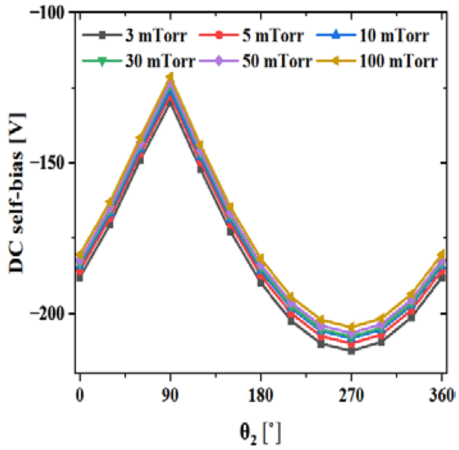


Fig. 2. Evolution of the DC self-bias voltage with phase shift at different pressures.

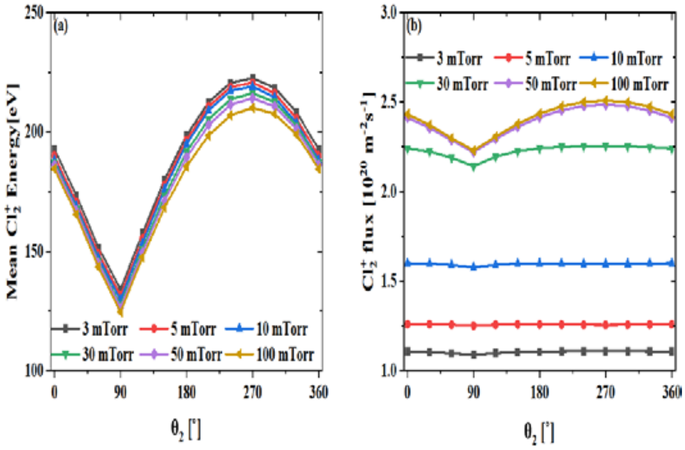


Fig. 3. Evolution of the (a) mean $Cl_2^+$ energy and (b) $Cl_2^+$ flux with phase shift at different pressures.