Current driven dual-frequency capacitively coupled discharge in chlorine

Shuo Huang[1] **and J. T. Gudmundsson**[1,2]

[1]University of Michigan - Shanghai Jiao Tong University Joint Institute,
Shanghai Jiao Tong University, 800 Dong Chuan Road, Shanghai 200240, China
[2]Science Institute, University of Iceland, Dunhaga 3, IS-107 Reykjavik, Iceland

Abstract

The effect of the control parameters of both the high and low frequency sources and secondary electron emission on a dual-frequency capacitively coupled chlorine discharge is systematically investigated using a hybrid approach consisting of a particle-in-cell/Monte Carlo simulation and a volume-averaged global model.

Introduction

The electronegative molecular chlorine discharge is widely used in plasma etching of semiconductors and metals.

Cl atoms are considered to be the primary reactant in plasma etching and the bombardment of positive Cl_2^+ and Cl^+-ions towards the substrate will significantly enhance the etching process.

Here we explore the dual-frequency capacitively coupled chlorine discharge using the particle-in-cell/Monte Carlo collision method [1, 2].

We apply a hybrid approach where a global model [3] is used to determine the dissociation fraction, n_{Cl}/n_g (n_{Cl} is the density of Cl atoms and n_g is the density of the feedstock gas), in the plasma before a particle-in-cell/Monte Carlo simulation deals with the kinetics of the discharge [1].

The species considered here are

- the ground state chlorine molecule $Cl_2(X^1\sum_g^+, v = 0)$
- the ground state chlorine atom $Cl(^2P_u)$
- the negative chlorine ion $Cl^-(^1S_g)$
- the positive chlorine ion $Cl^+(^3P_g)$
- the positive chlorine ion $Cl_2^+(^2\Pi_g)$

Both Cl_2 molecules and Cl atoms are treated as the initial background gas with uniform density in space and a Maxwellian velocity distribution at room temperature (T_g = 300 K).

We use the oopd1 simulation code and the included reactions and the relevant cross sections are described in detail in an earlier work [1]. There we explored a single-frequency discharge driven by a voltage source operated at 13.56 MHz within the pressure range 5 – 100 mTorr. The effect of driving current, driving frequency, secondary electron emission and adding a low frequency current source to a current driven discharge has also been explored [2].

Description of the simulation

The discharge is assumed to be sustained between two parallel plates, one of which is driven by a dual-frequency current source

$$J(t) = J_{hf}\sin(2\pi f_{hf}t) + J_{lf}\sin(2\pi f_{lf}t)$$

where f_{hf}, f_{lf}, J_{hf}, J_{lf} are the frequency and current density of the high- and low-frequency sources, respectively.

The diameter of the electrodes is assumed to be 10.2 cm and the gap length between the electrodes 2.54 cm. The discharge pressure is assumed to be 10 mTorr.

The simulation grid is uniform and consists of 1000 cells. The electron time step is chosen to be 1.84×10^{-11} s according to the stability criterion.

The simulation is run for 5500 high-frequency cycles for each case. The density profile and the electron heating rate profile are averaged over 54 high-frequency cycles, or approximately 4 low-frequency cycles, after the simulation runs to a stable state.

Results and discussion

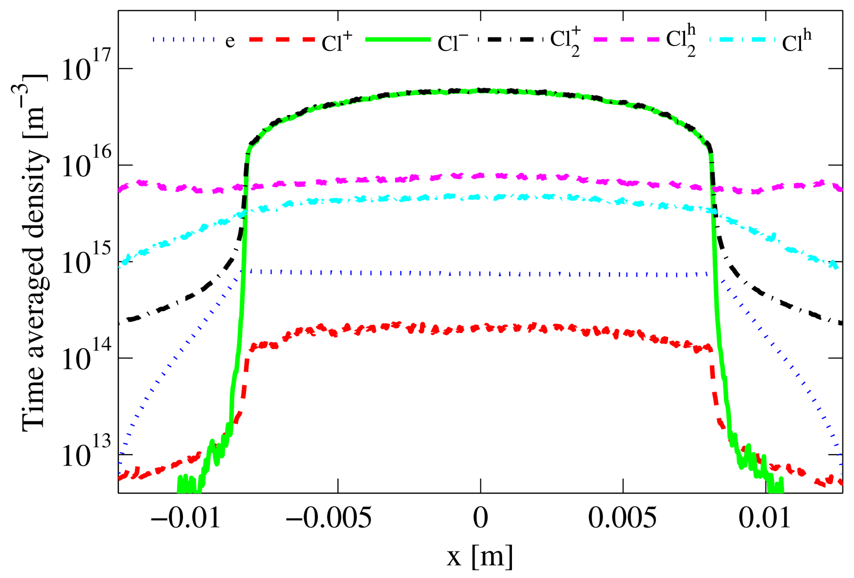

Figure 1: The time averaged density profile for a parallel plate capacitively coupled chlorine discharge at 10 mTorr with a gap separation of 2.54 cm by a 40 A/m^2 current source operated at 27.12 MHz. (Cl_2^h and Cl^h denote the high-energy Cl_2 molecules and Cl atoms with energy exceeding 1 eV, respectively.)

Figure 1 shows the time-averaged density profile for electrons, Cl_2^+, Cl^+, Cl, Cl and Cl_2 for a parallel plate capacitively coupled chlorine discharge at 10 mTorr with a gap separation of 2.54 cm by a 40 A/m^2 current source operated at 27.12 MHz.

The density profile is similar to the density profile obtained for recombination-dominated electronegative discharge.

In the bulk region, a high density of Cl ions is compared with a low electron density, which is the result of a very efficient electron- impact dissociative attachment, e + $Cl_2 \longrightarrow$ Cl + Cl

Thus, the electronegativity in the discharge center, $\alpha_0 = n_{Cl}/n_e$, reaches 83.5, which shows strong electronegative property of the discharge

Since the density of Cl ions is approximately two orders of magnitude higher than the density of electrons, the condition of quasineutrality in the plasma bulk necessitates commensurate densities of Cl_2^+ and Cl ions therein.

Figures 2 (a) and (b) show the IED of Cl_2^+ and Cl^+ ions with the addition of a low-frequency source, respectively.

As the low-frequency current density is increased from 0 to 4 A/m^2 the average energy of Cl_2^+ ions to the surface increases almost linearly.

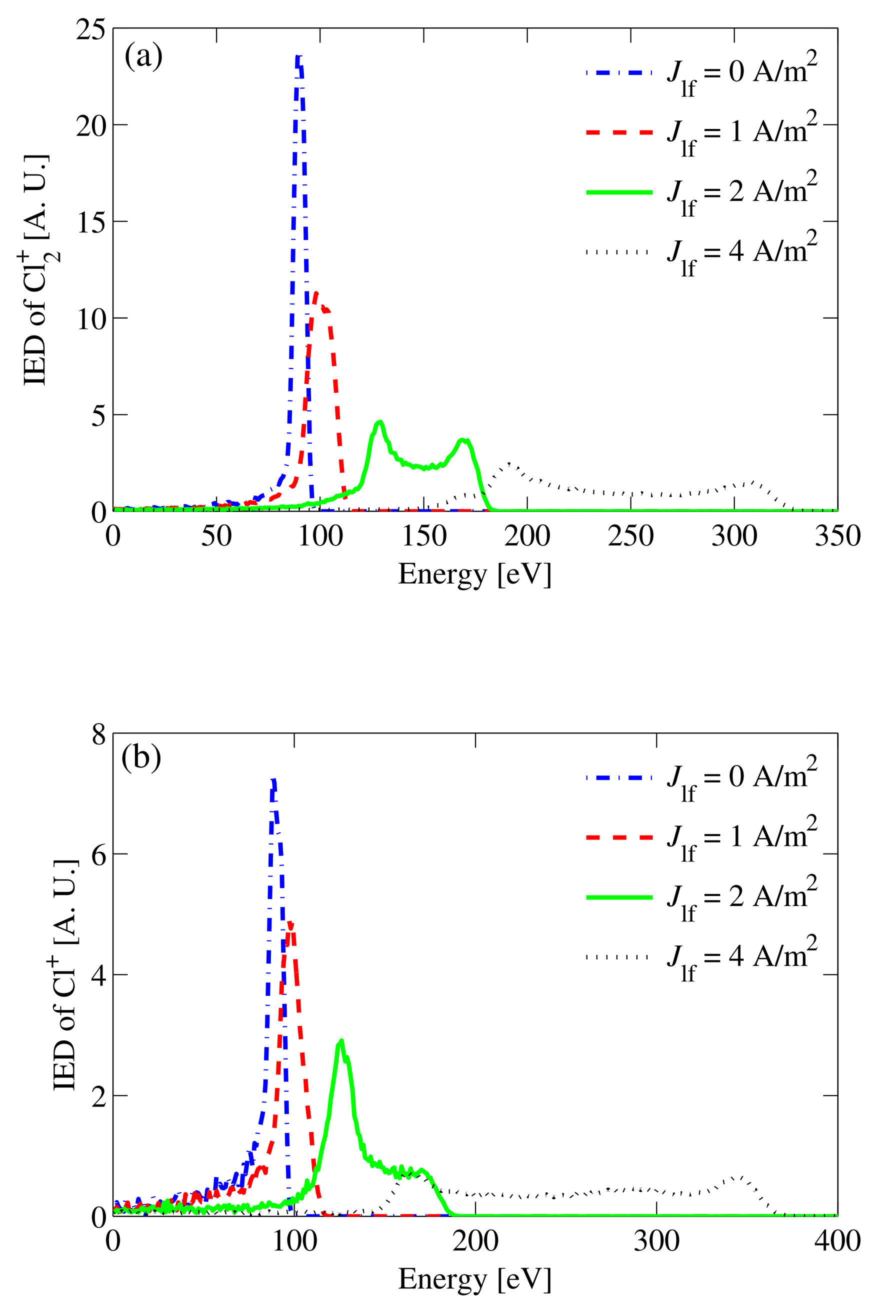

Figure 2: The IED of (a) Cl_2^+ ions and (b) Cl^+ ions at the powered electrode for a dual-frequency parallel plate capacitively coupled chlorine discharge at 10 mTorr with a gap separation of 2.54 cm. Here f_{hf} = 27.12 MHz and f_{lf} = 2 MHz, respectively. The high- frequency current density, J_{hf}, is maintained at 40 A/m^2.

In figure 3 we explore three cases for a current driven discharge with J_{hf} = 40 A/m^2 at 27.12 MHz and J_{lf} = 2 A/m^2 at 2 MHz with the secondary electron emission coefficient set to 0.0, 0.2 and 0.4.

As the secondary electron emission coefficient γ_{se} is increased in single-frequency discharge operated at 27.12 MHz, the average sheath potential decreases slightly since a lower voltage drop is needed there to ensure equal fluxes of electrons and ions.

The effect of the secondary electrons is very strong in the dual-frequency discharge and significantly larger than observed in the single-frequency discharge, as can be witnessed from the transition in the heating rate profile shown in figure 2 (a).

The addition of secondary electron emission amplifies the role of sheath heating due to secondary electrons accelerating through the large sheath fields.

Conclusions

- The effect of the secondary electron emission is very strong in the dual-frequency discharge and significantly larger than observed in the single-frequency discharge.

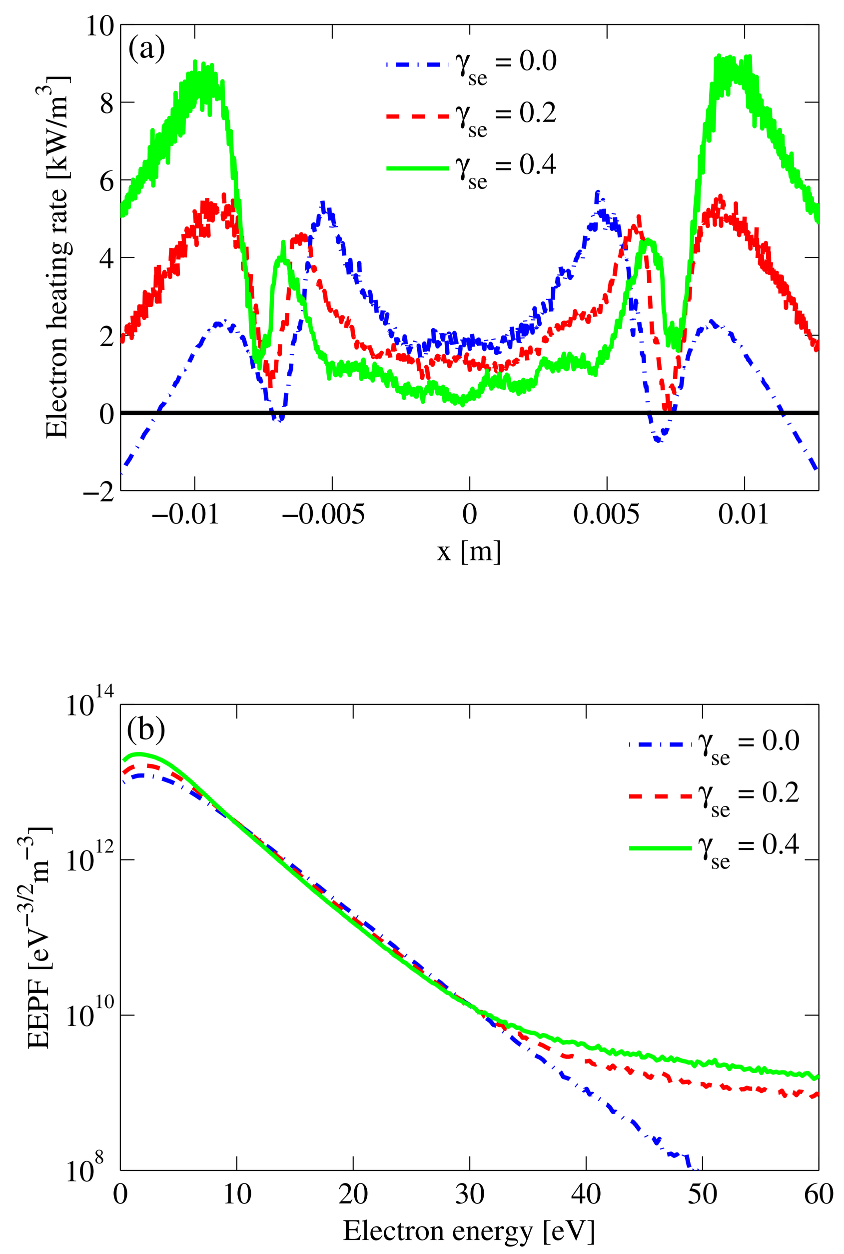

Figure 3: (a) The time averaged electron heating rate profile and (b) the electron energy probability function (EEPF) in the center of the discharge for a dual-frequency parallel plate capacitively coupled chlorine discharge at 10 mTorr, with J_{hf} = 40 A/m^2 at 27.12 MHz and J_{lf} = 2 A/m^2 at 2 MHz with the secondary electron emission coefficient set to 0.0, 0.2 and 0.4 and gap separation of 2.54 cm.

- As the low-frequency current density is increased from 0 to 4 A/m^2 the flux of Cl_2^+ ions to the surface increases only slightly while the average energy of Cl_2^+ ions to the surface increases almost linearly, which shows possible independent control of the flux and energy of Cl_2^+ ions by varying the low-frequency current in a dual-frequency capacitively coupled chlorine discharge.

References

[1] Shuo Huang and J. T. Gudmundsson. A particle-in-cell/Monte Carlo simulation of a capacitively coupled chlorine discharge. *Plasma Sources Science and Technology*, 22(5):055020, 2013.

[2] Shuo Huang and J. T. Gudmundsson. A current driven capacitively coupled chlorine discharge. *Plasma Sources Science and Technology*, 23(2):025015, 2014.

[3] E. G. Thorsteinsson and J. T. Gudmundsson. A global (volume averaged) model of a chlorine discharge. *Plasma Sources Science and Technology*, 19(1):015001, 2010.