Hybrid simulation of instabilities in a capacitively coupled RF CF_4/Ar plasma driven by a dual-frequency source

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Abstract: Instabilities in a capacitive Ar/CF_4 discharge driven by dual- frequency sources are investigated using a one-dimensional fluid/electron Monte-Carlo (eMC) hybrid model. Similar to the mechanism of the instable discharge driven by a single frequency waveform, the electron density increases while the electron temperature maintains intense oscillations in the bulk region, resulting in the appearance of the instability. But, driven by dual-frequency sources, the electron density, ionization rate, and other physical parameters all show not only periodic fluctuation but also spatial asymmetry.

Keywords: dual-frequency, capacitive radio frequency Ar/CF_4 plasmas, instability.

1. Introduction

Radio frequency capacitively coupled plasmas (RFCCP) are generally used for material processing industries such as film deposition or plasma etching processes due to their simple structures and the ability to produce a large area of uniform plasma [1,2]. Early, a large amount of work has focused on single frequency capacitively coupled plasma (SFCCP) sources, both in industry and research fields [3,4]. With the shrinking feature size in the semiconductor industries, traditional single source can no longer meet these demands, thus dual-frequency discharges play their critical role due to their ability to independently control ion energy and flux [5,6]. Instability is widely observed in experiment and industry, and this phenomenon may affect the stability of the process level and even the yield rate. However, most studies on instabilities focused on those driven by single frequency sources [7,8], so more attention is deserved on those in dual-frequency discharges. In this work, instabilities in a capacitively coupled Ar/CF_4 plasma driven by dual-frequency sources will be investigated.

2. Results and discussions

In this paper, we investigate a capacitively coupled CF_4/Ar (10/90) plasma at 100 mTorr based on a one-dimensional fluid model coupled with the electron MC method. For the base case, the dual-frequency voltage waveform applied at the lower electrode is $V(t)|_{x=0} = \phi_H \cos(2\pi f_H t) + \phi_L \cos(2\pi f_L t)$. Among this, the high/low frequencies are 18/2 MHz, and the voltages are 100/50 V correspondingly. The electrodes are parallel to each other and spaced by 2.8 cm. The spatio-temporal evolutions of the density distributions of electron, Ar^+, F^- and Ar^* with the corresponding voltage waveform are given in figure 1 (a)-(e), respectively. Similar to the discharge instability driven by single-frequency source [9], the densities of the electron, Ar^+ and F^- exhibit periodic fluctuations with a fluctuation period of about 45 high-frequency cycles (about 2.5 μs), except for the density of Ar^*, as shown in figure 1. Besides, the electron density is modulated by the high/low frequency sources and shows oscillations, meanwhile, the time variation of the electron density is no longer spatially symmetrical which differs from the single frequency case [9]. The electron density minima region is localized and oscillates between two electrodes, and the evident variations in the peak values of the electron density near the sheath boundary are also noticed. To explore the mechanism of the instabilities, 12 time points from T_1 to T_{12} are indicated by purple dashed line. Observing the discharge center, the electron density is higher during T_1-T_3 and T_7-T_9, while the F^- density becomes relatively lower, so the electronegativity (n_-/n_e) is reduced. At the same stage, the Ar^+ density shows a higher peak value, presenting an opposite trend to the negative ion density. However, the electron and Ar^+ densities reach relatively small values at the discharge center in the T_4-T_6 and T_{10}-T_{12} period, while the F^- density is higher and the electronegativity is enhanced.

The spatio-temporal evolutions of the electric field, electron power absorption rate, Ar ionization rate, Ar excitation rate, Ar^* ionization rate, CF_4 attachment rate (generate F^-), and the corresponding voltage waveform are schematically presented in figures 2 respectively. There is a difference in the bulk electric field strength at both sides of the minimal region of the electron density, resulting in asymmetric heating, ionization and spatial distribution of the electron density. Also with the electron diffusion, the minimal region of electron density moves up and down in the discharge region regularly. With the increasing of the high frequency, the electron density increases significantly, leading to the decrease of the electronegativity and the electron temperature in the bulk, and then the instability becomes less pronounced until it disappears. In addition, with the influence of instability in the case of 2/18 MHz, the ion fluxes also fluctuate and may have evident effects on surface processing.

3. Conclusions

In this work, the instabilities in a capacitive Ar/CF_4 discharge driven by a dual-frequency source are investigated. The instability period is about 45 high frequency cycles at the low/high frequencies of 2/18 MHz. Not only the periodic fluctuation in the discharge center as also found in instabilities of single driven source, but also the spatial asymmetry in the spatio-temporal distributions of the electron density, electric field, electron power absorption rate, ionization rate, and other physical parameters are noticed, under the influence of the dual-frequency driving.In this electronegative discharge, the asymmetric effect of the dual-frequency source on the bulk electric field and its electron heating makes the instability different. the .

In the future, we will study more about this instability phenomena with different discharge parameters and discuss further the influence of this unstable discharge on etching profiles.

4. Acknowledgements

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5. References

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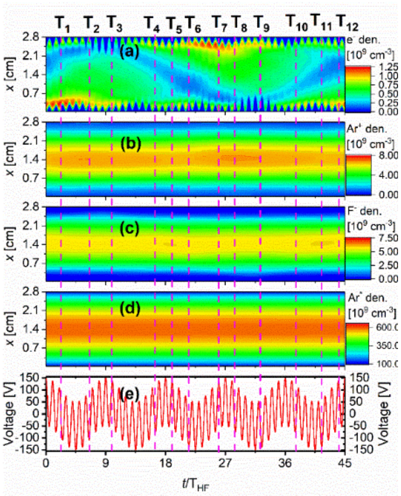

Fig. 1. Spatio-temporal density distributions of (a) electron, (b) Ar^+, (c) F^-, (d) Ar^* and (e) the voltage waveform. Times (purple dashed lines) of T_1~T_{12} are set to explore the periodic instabilities. Discharge conditions: gas mixture of CF_4/Ar (10/90) at 100 mTorr with a gap separation of 2.8 cm, sustained by 2 MHz/18 MHz, 50 V/100 V source supply

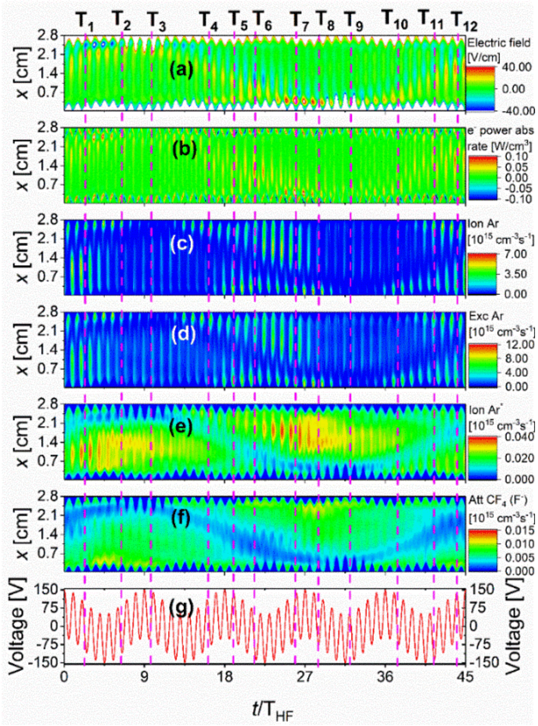

Fig. 2. Spatio-temporal evolutions of (a) electric field, (b) electron power absorption rate, (c) Ar ionization rate, (d) Ar excitation rate, (e) Ar^* ionization rate, (f) CF_4 attachment rate (generate F^-), and (g) applied voltage waveform. The discharge conditions are the same as those in figure 1