The ignition process of a pulse modulated dual-RF capacitively coupled plasma：role of low-frequency voltage amplitude

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Abstract: The effect of the low frequency (LF) voltage amplitude on the ignition process of a pulse modulated capacitively coupled dual rf argon discharge is investigated by multifold experimental diagnostics and particle in cell / Monte Carlo collision (PIC/MCC) simulations. It is found that at a higher LF voltage the ion-induced secondary electron emission from the electrode plays a key role in the electron avalanche during the ignition phase.

Keywords: pulse modulated capacitively coupled dual rf discharge, rf excitation, ignition phase.

Radio frequency (RF) plasmas operated at low pressure have been widely used in the semiconductor manufacturing industry, e.g. etching and deposition of materials. As the critical dimension of the semiconductor device approaches to atomic-scale and complex three-dimensional structures emerge [1]. To meet these urgent requirements, plasma reactors powered by a variety of sources have been proposed, e.g. dual-frequency driven plasma, RF plasma superimposed with the direct current (DC) source, tailored voltage waveform driven plasma, etc. Among these methods of electrically controlling plasmas, as research advancements continue, a pulse modulated plasma can be one of the most promising candidates for production of the high-performance semiconductor devices. Due to the fact that a pulse modulated plasmas can provide additional degrees of freedom for external control parameters (such as pulsed repetition frequency, duty cycle, amplitude-modulated form, etc.), they can improve the independent control of certain plasma parameters, such as the flux and energy of charged particles and radical composition, and reduce plasma-induced damages (PIDs) [2,3]. Meanwhile, the dual-frequency CCRF is more effective in the etching process in conventional continuous-wave (CW) plasma, since it not only produces higher plasma density, but also can control the ion energy and flux over a certain parameter range independently. Therefore, pulse modulated dual rf plasma that combines advantages of dual frequency and pulse discharge may be introducing better effects for the semiconductor manufacturing industry. However, to our best knowledge, there have been fewer studies on pulse modulated dual RF plasma, especially for the ignition phase.

In this work, we investigate the ignition processes of a pulsed dual-frequency CCRF discharge operated at different low-frequency (LF) voltage amplitudes using multiple time-resolved diagnostic tools, with a particular attention on the comparative analysis of the ignition processes at different LF voltages. Meanwhile, the ignition process is followed by a 1D3V electrostatic PIC/MCC simulations, which are initialized with very low electron/ion densities.

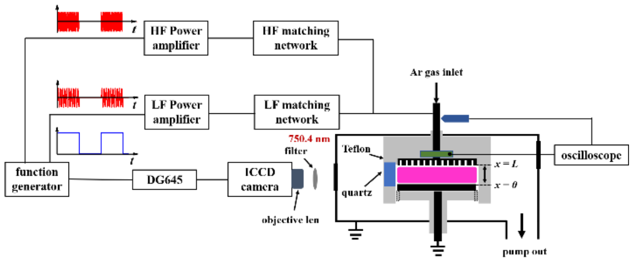

Fig.1 Schematic of a pulse-modulated dual-RF capacitively coupled plasma reactor, complemented by a phase-resolved optical emission spectrometer and electrical measurement systems.

The diagram of the plasma reactor and diagnostic tools are illustrated in fig.1. The argon plasma is generated between two circular parallel-plate aluminum electrodes with a 10 cm diameter and separated by 2.5 cm. The discharge region is enclosed by a Teflon liner in order to minimize the DC self-bias and avoid parasitic discharges occurring outside of the interelectrode glow region. A function generator is used to output two pulse modulated RF signals with a locked phase at 0. The high frequency (HF) is 12.5 MHz, while the low frequency (LF) is 2.5 MHz. The two signals are amplified by two amplifiers and delivered to the top electrode via two fixed matching boxes, respectively. Meanwhile, a synchronized square signal of the function generator is used to trigger a pulse delay generator (DG645), which triggers an intensified charge coupled device (ICCD) camera for measurement of the spatiotemporally resolved optical emission intensity since the start of each pulse. The voltage waveforms and current waveforms at the power feeding point are monitored by a voltage probe and current probe, respectively.

The simulation is based on the particle in cell method, complemented with Monte Carlo treatment of collision processes (PIC/MCC). The electron-surface interactions are described by a realistic model, which considers the elastic reflection and the inelastic backscattering of electrons, as well as electron-induced second electron emission (see figure 2). More details of the realistic model can be found in Refs. [4]. Meanwhile, the ion-induced second electron emission coefficient is fixed to be 0.2 in order to get a good match with experimental results.

In Fig.2, the right and left panels show the time evolution of the HF and LF electrical parameters determined experimentally, respectively. The plasma ignition process can be analysed by dividing this process into the pre-ignition, the ignition and the post-ignition phases (The blue part is the duration of pre-breakdown, the yellow part indicates the breakdown phase, and the pink part is the post-breakdown phase) [5,6].

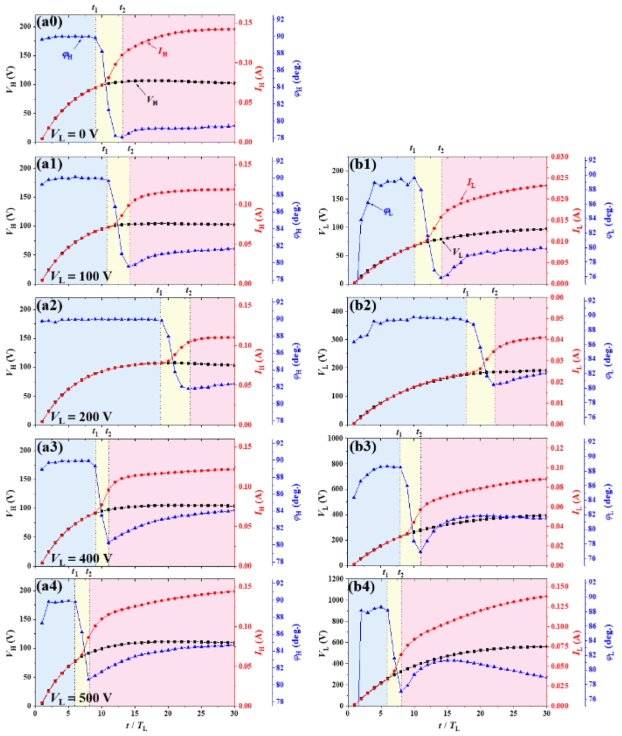

Fig.2 Experimental results obtained during the first 30 LF cycles: the amplitudes of the HF and LF voltages, V_H and V_L, the amplitudes of the HF and LF currents, I_H and I_L, and the relative phases between the voltage and the current, φ_H and φ_L. The left-hand panels are the HF components, while the right-hand panels are the LF ones.

During the pre-breakdown phase, both I_H and I_L are dominated by displacement current and closely follows the increasing V_H and V_L for all the V_L. Meantime, φ_H first increases lightly, and then stays at 90 degree for different duration depending on V_L. The duration of pre-breakdown become longer when V_L increases from 0V to 200V, suggesting that the ignition is delayed. Because the electron loss is enhanced in the presence of a low LF voltage However, the plasma ignition is advanced by increasing V_L to 500V, due to enhanced electron avalanche by the ion-induced secondary electron emission.

During the breakdown phase, I_H exhibits a fast growth, due to rapidly increasing charge density between the electrodes, while V_H increases more smoothly for various V_L. The degree that I_H increases depends on the onset time of the ignition phase. At a low or high V_L, the plasma is ignited earlier, see, e.g., Fig.2(a0) and Fig.2(a5). By contrast, at moderate V_L, e.g., V_L =200V (see fig.2(a2)) the plasma is ignited later than that at a low or high V_L and I_H increases less significantly.

In the post-breakdown phase, the electrical parameters tend to stabilize. However, the value of φ_L shows a peak and does not reach stability at V_L = 400V and 500V. This reason is that the resistance of the discharge system increases, due to increased electron density by the high energy secondary electrons induced by ions bombardment.

Conclusions

The effect of the LF voltage amplitude on the time evolution of the plasma and electrical parameters during the ignition phase of a pulse modulated dual-frequency capacitively coupled rf argon discharge has been investigated via experimental diagnostics and PIC/MCC simulation. We found that V_L affects the duration of pre-breakdown significantly, which reason is that the various electron multiplication efficiency occurs at different V_L. For lower V_L, e.g. $V_L \leqslant$ 200 V, the loss efficiency of electrons increases with V_L, which lead to a slower increase in electron density, and a delay in the ignition moment. By further increasing V_L to 400 V or 500 V, the ignition moment is advanced, mainly due to ionization is enhanced by collision between high-energy ion-induced secondary electrons and neutral argon particles in the bulk region.

Acknowledgements

This work has been financially supported by the National Natural Science Foundation of China (NSFC) (Grants No. 12275043 and 11935005).

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