Scaling of neutral, ion and photon fluxes in pulsed inductively coupled plasmas formed in Ar/O_2 mixtures

A. R. Gibson, T. Carpenter, M. Osca Engelbrecht, C. P. Ridgers
York Plasma Institute, School of Physics, Engineering and Technology, University of York, York, United Kingdom

Abstract: In this contribution, 0-D plasma chemical kinetics simulations are used to study the scaling of neutral, ion and vacuum-ultraviolet (VUV) photon fluxes in pulsed inductively coupled plasmas at low pressure. Simulations predict that variation of pulse parameters, such as average power and duty cycle, allows for decoupling between the fluxes of reactive neutrals, ions and VUV photons.

1. Introduction

Low pressure plasmas formed in Ar/O_2 mixtures are of interest for state-of-the-art plasma enhanced atomic layer deposition (PE-ALD) processes [1, 2]. These processes can be carried out in either inductively- or capacitively coupled plasma sources. In PE-ALD of SiO_2, oxygen-containing plasmas produce reactive oxygen species (ROS, e.g. O, $O_2(a^1\Delta_g)$, $O_2(b^1\Sigma_g^+)$) that oxidize precursors on surfaces to form an SiO_2 layer. In the PE-ALD mechanism for SiO_2 deposition developed by Qu et al [1], different ROS are proposed to induce different surface reactions with distinct probabilities, and as such may not necessarily be treated as equivalent drivers of process rate or quality. Ion fluxes to surfaces play an important role in material quality, with high ion energies leading to sputtering and affecting the properties of the deposited material. Similarly, VUV photon fluxes have also been proposed to influence the quality of the deposited layers.

To optimize the properties of materials deposited by PE-ALD, control strategies for fluxes of ROS, ions and VUV photons are required. One prominent control strategy in industrial plasma reactors is the pulsing of the input power supply. Here, pulse parameters including, maximum / time-averaged power, pulse repetition frequency and pulse duty cycle act as free parameters to control particle fluxes to surfaces.

In this contribution, 0-D plasma-chemical kinetics simulations, inclusive of a collisional radiative model for VUV emission from O atoms, are used to study the scaling of particle fluxes to surfaces in pulsed inductively coupled plasmas.

2. Methods

The formulation of the model and the reaction mechanism for Ar/O_2 used in this work are described in detail and compared with experimental measurements in [3]. Here, the model is used to carry out simulations in a modified GEC reference cell geometry, where the power to the inductive coil is pulsed. Simulations are carried out for variations of gas pressure, gas mixture and pulse profile characteristics. For the latter, pulse-averaged power (50 – 600 W), pulse repetition frequency (1 – 50 kHz) and duty cycle (5 – 90%) are the key variable parameters.

3. Results and Discussion

Figure 1 shows the variation of O atom, positive ion and VUV photon fluxes to surfaces for the base case simulation, as a function of time throughout one pulse period, after a pulse-periodic steady state has been reached. In general, the flux of O atoms (and other ROS) vary less as the power is switched on and off in comparison with ion and VUV photon fluxes. Because of this, variation of the pulse parameters enables a degree of decoupling between the fluxes of different components. Increasing the pulse-averaged power is found to increase the relative importance of VUV photon fluxes in comparison to both O atom and ion fluxes. On the other hand, increasing the duty cycle leads to an increase in the importance of VUV photon fluxes in comparison to positive ions, but a decrease in the importance of photons in comparison to reactive neutrals.

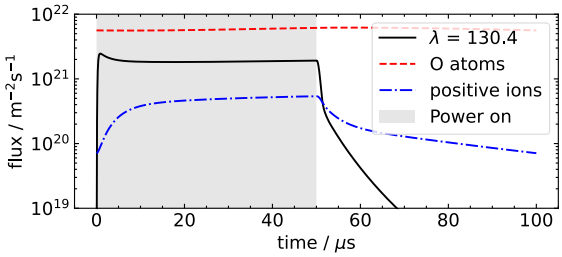

Fig. 1. Fluxes of O atoms, positive ions and VUV photons to surfaces during a single pulse cycle. Conditions: 100% O_2, pressure = 5 Pa, pulse-averaged power = 400 W, pulse repetition frequency = 10 kHz, duty cycle = 50%

4. Conclusion

The influence of pulsed operation on the fluxes of neutrals, ions and VUV photons is studied in an inductively coupled plasma system, operated in variable Ar/O_2 mixtures. It is found that the relative importance of the fluxes of different components can be controlled by the pulse shape. Implications for these results of PE-ALD applications will be discussed.

References

[1] C. Qu et al., J. Vac. Sci. Technol. A **39**, 052403 (2021)
[2] K. Arts et al., Chem. Mater., **33**, 5002-5009 (2021).
[3] M. Osca Engelbrecht et al., Plasma Sources Sci. Technol., **33**, 095008 (2024).