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Analysis of stagnation point flow within an inductively coupled plasma reactor for the enhancement of deposition methodologies

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Plasma-Enhanced Atomic Layer Deposition (PEALD) is a pivotal technique for achieving high-quality thin films with precise thickness control and superior conformality. In PEALD processes operating within the Torr pressure regime, optimizing plasma transport and uniformity is crucial to enhancing film deposition efficiency [1]. Among the factors influencing plasma behavior, the gas flow pattern—particularly stagnation point flow (Figure 1)—plays a critical role in governing electron and ion transport. Nevertheless, understanding how process parameters such as input power, gas pressure, and gas flow rate influence plasma distribution remains a significant challenge.

In this study, a fluid-plasma model is employed to numerically investigate the spatial distribution of plasma parameters within a PEALD reactor. Both pure argon (Ar) plasma and oxygen/argon (O_2/Ar) plasma are considered, as they are commonly utilized in PEALD applications. The simulations incorporate a detailed Ar chemistry model, enabling rigorous comparisons between predicted plasma densities and experimental Langmuir probe measurements.

Special focus is given to two distinct regions of the reactor: the ICP source region, where electron heating is concentrated, and the diffuser region, where the substrate is located. Through systematic parametric analysis, the effects of input RF power, gas pressure, and gas flow rate on plasma transport are elucidated. Furthermore, geometric modifications to the reactor are proposed to improve plasma uniformity, specifically addressing the issue of localized ion flux concentration at the reactor center. The findings offer valuable insights into optimizing PEALD conditions for enhanced plasma transport and uniform film deposition.

Initially, a comprehensive chemical reaction set for Ar plasma was established. Due to the high collision frequency characteristic of the operating pressure range, energy transfer among reactive species is highly active, necessitating the adoption of a detailed Ar chemistry framework. This approach resulted in simulation outcomes that closely matched experimental plasma density measurements obtained via Langmuir probes, thereby validating the model.

Plasma transport phenomena were systematically analyzed in both the ICP source region (proximate to the antenna coil) and the diffuser region. The influence of key operational parameters—including RF power, gas pressure, gas flow rate, and reactor geometry – was rigorously evaluated. Additionally, spatial distributions of the reactive species $O(^3P)$ and $O(^1D)$ in O_2/Ar plasma were examined, given their critical roles in oxidation reactions during PEALD. The key findings are summarized as follows:

1. *Effect of RF Power*

Plasma density in the ICP source region increases significantly with RF power, leading to elevated electron temperatures and enhanced ionization rates. Strong inductive heating in this region facilitates convective transport of energy toward the diffuser region.

2. *Effect of Gas Pressure*

Increasing gas pressure results in a reduction of electron temperature and weakening of the electric field, culminating in a decrease in plasma density. Conversely, higher gas pressure simultaneously elevates the gas temperature due to increased collisional heating.

3. *Effect of Gas Flow Rate*

Higher gas flow rates enhance ion flux along the flow direction, thereby improving plasma transport efficiency into the diffuser region. These results emphasize the critical importance of precise gas flow control in plasma optimization.

In conclusion, appropriate adjustment of RF power, gas pressure, and gas flow rate enhances plasma transport into the diffuser region and reinforces stagnation point flow characteristics. However, stagnation point flow inherently causes excessive ion flux concentration at the reactor center, compromising plasma uniformity. To mitigate this effect, two modified reactor geometries were investigated. It was found that the installation of a central baffle substantially improved the uniformity of Ar^+ surface flux. Similar improvements were observed in O_2/Ar plasma conditions, where baffle installation led to more uniform distributions of key reactive species, including $O(^3P)$ and $O(^1D)$.

References
[1] S. Jo and H. J. Kim, Phys. Fluids 37, 013634 (2025)

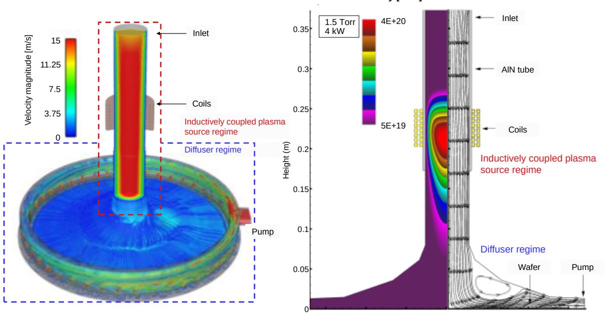

Figure 1. Stagnation point flow in the PEALD reactor.