Plasma Edge Simulations by Finite Elements using COMSOL

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Introduction

Large area PECVD depositions (>1m²)

Application

Silicon deposition
Thin film solar cells
Flat displays
Problems of large area plasma depositions

Homogeneity (… of layer thickness, structure)

Gas flow
Electrical parameters
**Edge effects**

......
Problems of large area plasma reactors

- Powder formation
- Inhomogeneity
- Contamination
- Device quality
- Gas flow/pumping
- RF circuit/connection
- RF electrode-ground transition
- Substrate
Plasma reactor parameters and geometry

- Capacitively coupled RF plasma reactor
- Electrode gap 0.03 m
- Frequency 13.56 MHz
- RF 200V_{pp}
- Gas Argon
- Pressure 1 mbar

Simplified geometry

Corner

Grounded electrode

Homogeneous part

RF
Basic equations and boundary conditions

2D Fluid equation

electron continuity: \[ \frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma_e = k_{ion} n_e N; \quad \Gamma_e = -\mu_e n_e E - D_e \nabla n_e \]

ion continuity: \[ \frac{\partial n_i}{\partial t} + \nabla \cdot \Gamma_i = k_{ion} n_e N; \quad \Gamma_i = \mu_i n_i E - D_i \nabla n_i \]

electron energy continuity, \( (n_e \varepsilon) \) is the energy density in eV \( \cdot \) m\(^3\):
\[ \frac{\partial (n_e \varepsilon)}{\partial t} + \nabla \cdot \Gamma_w = -\Gamma_e \cdot E - K_{loss} n_e N; \quad \Gamma_w = -\frac{5}{3} \mu_e (n_e \varepsilon) E - \frac{5}{3} D_e \nabla (n_e \varepsilon) \]

- \( \Gamma_e \cdot E = \mu_e n_e (E_x^2 + E_y^2) + D_e \left( \frac{\partial n_e}{\partial x} E_x + \frac{\partial n_e}{\partial y} E_y \right) \)

Poisson's equation: \[ \nabla^2 V = -\frac{e}{\varepsilon_0} (n_i - n_e); \quad E = -\nabla V \]
Numerical procedures

Meshing: Quadrilateral mesh
Boundary mesh option
Optimizing (calculation time, memory…)

Solver: Spoole (time dependent)
A simple case

Geometry

Meshing

Mesh quality
Meshing and convergence

Mesh

Convergence

Important!
Investigated simplified geometries

<table>
<thead>
<tr>
<th>Open geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed geometry</td>
</tr>
<tr>
<td>D=40mm</td>
</tr>
<tr>
<td>D=20mm</td>
</tr>
<tr>
<td>D=10mm</td>
</tr>
<tr>
<td>Asymmetric</td>
</tr>
<tr>
<td>D=15mm</td>
</tr>
<tr>
<td>Symmetric</td>
</tr>
<tr>
<td>D=15mm</td>
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</tbody>
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Benchmark with 1D
First result

Maximum of the electron density

Maximum of ionisation rate

Experimental evidence
Powder formation
Presence of a Double Layer?

Contour plot electron density

Line plots

Potential \( n_e \) \( n_p \)

Presence of a Double Layer

Space charge density
Time dependent space charge density

RF voltage

Space charge density

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Plasma Processing

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Double Layer and Sheath

Graphical representation showing the distributions of space charge density and electron density across different regions, labeled as 'a' and 'b'. The regions are denoted as Double Layer (DL) and Sheath.
An other view....
The symmetric case

Electron density
Electrical potential
Space charge density

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Fundamental role of corners

High ionisation rate

Different role of concave and convex corners

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Role of the particle fluxes

Electron and ion flux distribution

Role of corners
Known problem from ion implantation
Influence of the reactor edge

Corners are an important design element
Important parameter:

Sheath thickness

Geometrical dimensions of the corner

Other design parameters which influence the plasma

Rounding of the corners

Material (Insulator…)

Spacing (dimensions)
Conclusion

Simulations are a very useful method for plasma physics and plasma edge design

COMSOL software is well adapted

- Simplified geometries
- Meshing
- Convergence
- Insight in the physics of corners
- Insight into the physics of RF reactors
- Design of plasma edge