Fluid Modelling of Plasma Discharge at Low Pressures

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Abstract

Discharge characteristics of argon microwave plasma were investigated by using fluid simulation of a MPACVD (Microwave Plasma Assisted Chemical Vapor Deposition) reactor based on finite elements method at low pressure (25-250) Pa. The microwave power was 2.45 GHz TM mode transmitted through the resonant cavity. Microwave power and pressure were considered simulation parameters and argon was used for working gas.

A self-consistent fluid model was developed in Comsol Multiphysics Plasma Module for studying the discharge phenomena. The 2D plasma fluid model gives a complete description of spatial-and time evolution of the discharge characteristics such us: electron density and electron temperature. Simulation results show a strong effect of input parameters on the species densities distribution in the plasma.

Keywords : *fluid model, Finite element method, COMSOL MWP module, microwave plasma.*

1. Introduction

The MPACVD processes involve many complex and highly coupled phenomena. Thus, the numerical simulation is an indispensable tool to understand the plasma behavior inside the reactor, and to improve the knowledge of deposition or etching **[1, 2, 3]**.

We choose the plasma fluid model to characterize the plasma due to his flexibility and speed of computations **[4, 5]**. Plasma fluid model allows us to estimate the time-variation of electron density and electron temperature. These quantities are crucial to characterize the plasma and its applications in syntheses or surface treatment **[6]**.

In this present work, we applied the finite element method for numerical simulation of a pure argon discharge characteristics in a MPACVD reactor using COMSOL Multiphysics software. The main objective of this work is to understand the diverse transfer phenomena related to species existing in this type of discharge in order to control these phenomena and predict the physicochemical properties of the microwave discharge.

The paper is organized as follow, equations solved with the fluid plasma model are considered in section 2 while section 3 is devoted to describe the geometry modeled. In section 4, the numerical results and discussion are presented. Finally, we kept section 5 for a conclusion.

2. Model Description

The electron density and mean electron energy are computed by solving a pair of drift-diffusion equations for the electron density and mean electron energy. Convection of electrons due to fluid motion is neglected **[6, 7]**:

- Electron density equation:

$$\frac{\partial n_e}{\partial t} + \nabla.\boldsymbol{\Gamma_e} = R_e - (\mathbf{u}.\nabla)n_e \quad \textbf{(1)}$$

$$\boldsymbol{\Gamma_e} = -(\boldsymbol{\mu_e}.\mathbf{E})n_e - \mathbf{D_e}.\nabla n_e \quad \textbf{(2)}$$

- Mean electron energy equation:

$$\frac{\partial n_\varepsilon}{\partial t} + \nabla.\boldsymbol{\Gamma_\varepsilon} + \mathbf{E}.\boldsymbol{\Gamma_e} = R_\varepsilon \quad \textbf{(3)}$$

$$\boldsymbol{\Gamma_\varepsilon} = -(\boldsymbol{\mu}_\varepsilon.\mathbf{E})n_\varepsilon - \mathbf{D}_\varepsilon.\nabla n_\varepsilon \quad \textbf{(4)}$$

- Poisson's equation:

$$\mathbf{E} = -\nabla V \quad \textbf{(5)}$$

Where n_e denotes the electron density $(1/m^3)$, R_e is the source term (electron rate expression) in unit $(1/(m^3.s))$, $\mathbf{u}$ is the electronic speed vector (m/s), $\boldsymbol{\Gamma_e}$ is the electron flux (1/(m^2.s)), μ_e is the electron mobility $(m^2/(V.s))$, $\mathbf{E}$ is the electric field (V/m), D_e is the electron diffusivity (m^2/s), n_ε denotes the electron energy density (V/m^3), R_ε is the energy loss/gain due to inelastic collisions (V/ $(m^3.s)$), $\boldsymbol{\Gamma_\varepsilon}$ is the electron energy flux (1/ (m^2.s)), μ_ε is the electron energy mobility $(m^2/(V.s))$, D_ε is the electron energy diffusivity (m^2/s) and V is the electric potential (Volt). The following relationships hold **[7, 8]** for Maxwellian electron energy distribution function:

$$D_e = \mu_e T_e \quad \textbf{(6)}$$

$$D_\varepsilon = \mu_\varepsilon T_e \quad (7)$$

$$\mu_\varepsilon = \left(\frac{5}{3}\right)\mu_e \quad (8)$$

T_e is the electron temperature (eV) depending on the mean electron energy, it is defined as:

$$\tilde{\varepsilon} = \frac{n_\varepsilon}{n_e} \quad (9)$$

$$T_e = \left(\frac{2}{3}\right)\tilde{\varepsilon} \quad (10)$$

3. Geometry Modeled

The plasma is maintained by an electromagnetic wave (2.45GHz) that propagates into a cylindrical waveguide in TM mode. Here we are interested on the interaction of the electromagnetic wave with the argon gas inside the microwave cavity reactor. The MPACVD reactor was simulated in 2D space geometry as shown in Fig-1.

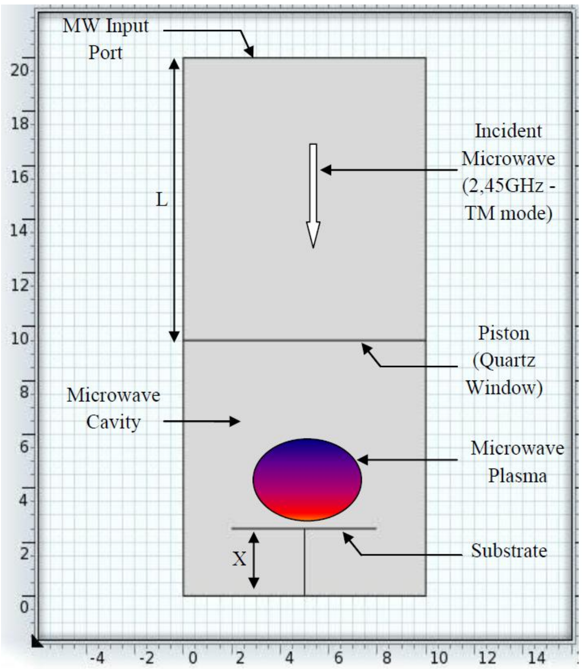

Fig-1. *The diagram of 2D geometry modeled*

4. Numerical Results and Discussion

The simulation results shown in this section were all performed in the geometry presented in the Fig-1. The pressure of the simulated Ar gas was in the range (25-250) Pa.

The MWP module developed in this study provides the effect of the input parameters such as microwave power and gas pressure on the plasma discharge characteristics. The electron density in argon plasma discharge is plotted as a function of the incident microwave power, as shown in Fig-2. Results indicate that, at a given gas pressure, electron density increases linearly with microwave power. For example, at a pressure of 1.95Torr, the electron density increases from $7.84\text{x}10^{17}\ m^{-3}$ to $2.76\text{x}10^{18}\ m^{-3}$ when the incident power increases from 400W to 1600W.

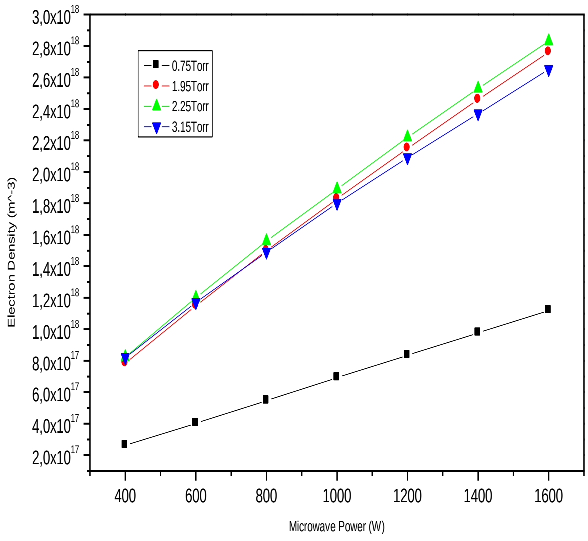

Fig-2. *Dependence of electron density on microwave Power for different argon pressure at 19mm above the substrate*

We can also note that, at given incident power, electron density increases with increase of gas pressure to 2.25Torr. If the pressure is further increased (beyond 2.5Torr), the electron density decreases. This behavior is better presented in Fig-3, representing plasma density as function of gas pressure for several microwave powers.

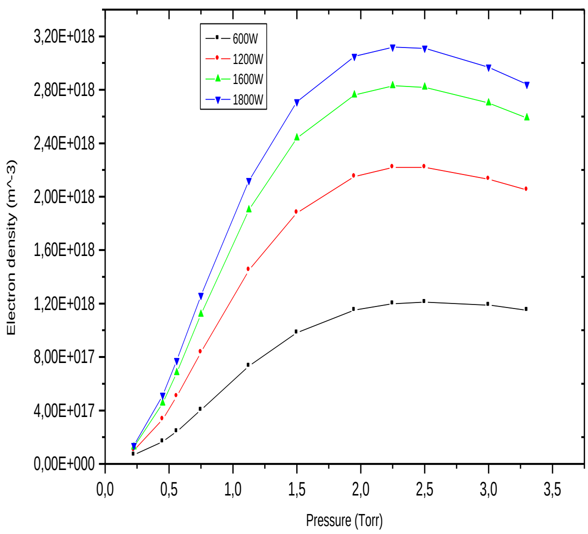

Fig-3. *Dependence of electron density on argon pressure for different incident power at 19mm above the substrate*

It is clearly seen that, keeping the positions of substrate and piston constant, we should adjust simultaneously the pressure and the incident power, in order to maintain the plasma discharge volume and to control its location inside the cavity.

5. Conclusion

In this paper, a fluid plasma model for simulating argon microwave plasma characteristics was performed. The simulation results were obtained at low pressures by solving the electron density equation, mean electron energy equation and Poisson's equation. The governing equations are solved in two-dimensional geometry using the finite element method. Numerical results have allowed us to study the effect of operating input parameters, especially gas pressure and microwave incident power on the characteristics of the plasma discharge such as: electron density. The calculated simulation results showed a good satisfactory agreement with experimental and numerical results.

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