

## A study of asymmetrical effects in a 3D Inductively Coupled Plasma discharge simulation of including multiphysics

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A three-dimensional plasma simulation for an inductively coupled plasma (ICP) discharge based on the fluid model for the semiconductor manufacturing process is conducted in this study. Heat transfer and gas flow are merged to the plasma simulation to consider physical phenomena simultaneously.

It is well-known that the electron energy distribution function (EEDF) is important in determining important coefficients such as electron mobility, diffusion coefficient, electron-neutral reaction rates and so on. Therefore, the EEDF was obtained by two-term Boltzmann Solver using space-averaged plasma properties (electron density, electron temperature, gas temperature, ionization degree, molar fraction, etc).

The effects of asymmetrical structure of the antenna coil and that of the discharge chamber are investigated. 3D effects were observed, which could not be found in the 2D axisymmetric simulation.

### 1. Introduction

Inductively Coupled Plasma (ICP) is widely used in microelectronic processes, because it can generate high density and good uniformity of plasma. Testing real plasma is aligned with high financial costs, so demand for a simulation model is high.

This study is presents a 3-dimensional ICP discharge simulation based on the fluid model in a semiconductor manufacturing process. Plasma properties are investigated by merging the effects of magnetic fields caused by coil, and gas flow which play an important role in realistic fabrication.

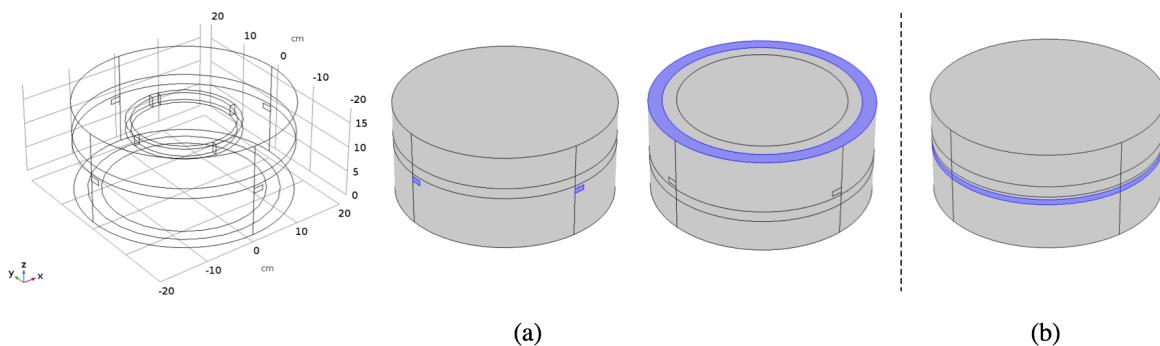
Usually, most of plasma simulations in semiconductor process assume the electron energy distribution function as a Maxwellian EEDF, which can obtain approximate values in a relatively short time. But in this study, we applied the Boltzmann EEDF that is calculated from

a two-term Boltzmann Solver with plasma properties such as electron density, gas temperature, molar fraction, etc.

Moreover, there are many studies conducted by using a 2-dimensional axisymmetric geometry. However, this study considers asymmetrical effects derived from gas inlet structure by conducting a 3-dimensional simulation.

## 2. Model description

The study is conducted by using a simulation tool called COMSOL Multiphysics. Merged physics are plasma (plas) interface, magnetic fields (mf) interface and laminar flow (spf) interface for obtaining more accurate results.



[ Figure 1. Geometry : (a) Asymmetric case, (b) Symmetric case ]

The overall geometry is shown in Fig.1. The radius of plasma chamber is 20cm and the height is 10cm. The 1-turn coil which has a radius of 10cm is placed on the 2cm-heighed dielectric. In the asymmetric case, the gas inlet structure has a width of 1cm, a height of 2cm and is separated in four parts on the plasma chamber wall like in the real semiconductor manufacturing process.

The bottom surface of the plasma chamber contains 3 parts. There is an electrode on which the wafers will be placed with a radius of 15cm. The 2.5cm wide dielectric material is placed on the outer layer of that electrode. At the outer layer of the dielectric material, a gas outlet with a width of 2.5cm is placed.

The wall of plasma chamber except gas inlet and outlet is grounded. The power source is one-turned coil with a 50A input source. The dielectric material underneath this coil has a relative permittivity of 5.7, thus serving as an electrical insulation.

Drift-diffusion approximation was used to describe the electrons and the continuity. Electron energy equations were applied.

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \boldsymbol{\Gamma}_e = (S - L)_e, \quad (1)$$

$$0 = \frac{en_e}{m_e} \nabla V - \frac{1}{m_e} \nabla (n_e T_e) - v_{eN} \boldsymbol{\Gamma}_e \quad (2)$$

$$\frac{\partial}{\partial t} \left( \frac{3}{2} n_e T_e \right) + \nabla \cdot \left( \frac{5}{2} \boldsymbol{\Gamma}_e T_e - \frac{5}{2} \frac{en_e T_e}{m_e v_{eN}} \nabla T_e \right) - e \nabla V \cdot \boldsymbol{\Gamma}_e + P_{e,loss} = P_{abs}, \quad (3)$$

where  $n_e$ ,  $\boldsymbol{\Gamma}_e$ ,  $(S - L)_e$ ,  $\mu_e$ ,  $\mathbf{E}$ ,  $D_e$ ,  $m_e$ ,  $v_{eN}$ , and  $V$  are the electron density, electron flux, difference between the source of electron and the loss of electron, electron mobility, electric field, electron diffusivity, electron mass, collision frequency between electrons and neutral particles, and electric potential, respectively.  $P_{e,loss}$  is the energy exchange during the collisional processes, and  $P_{abs}$  is the absorbed power owing to inductive discharge.

The ion is calculated by adapting the drift-diffusion approximation.

$$\frac{\partial n_i}{\partial t} + \nabla \cdot \boldsymbol{\Gamma}_i = (S - L)_i, \quad (4)$$

$$\boldsymbol{\Gamma}_i = -n_i (\mu_i \cdot \mathbf{E}) - D_i \nabla n_i, \quad (5)$$

where  $n_i$ ,  $\boldsymbol{\Gamma}_i$ ,  $(S - L)_i$ ,  $\mu_i$ , and  $D_i$  are the ion density, ion flux, difference between the source of ion and the loss of ion, ion mobility, and ion diffusivity, respectively.

In addition, the energy and mobility of neutral species were considered.

$$\rho (\mathbf{u}_n \cdot \nabla) \mathbf{u}_n = \nabla \cdot \left[ -p \mathbf{I} + \mu_n (\nabla \mathbf{u}_n + (\nabla \mathbf{u}_n)^T) - \left( \frac{2}{3} \right) \mu_n (\nabla \cdot \mathbf{u}_n) \mathbf{I} \right] \quad (6)$$

$$\nabla \cdot (\rho \mathbf{u}_n) = 0, \quad (7)$$

where  $\rho$ ,  $\mathbf{u}_n$ ,  $p$  and  $\mu_n$  are the neutral density, neutral velocity, gas pressure, and dynamic viscosity of neutral flux, respectively.

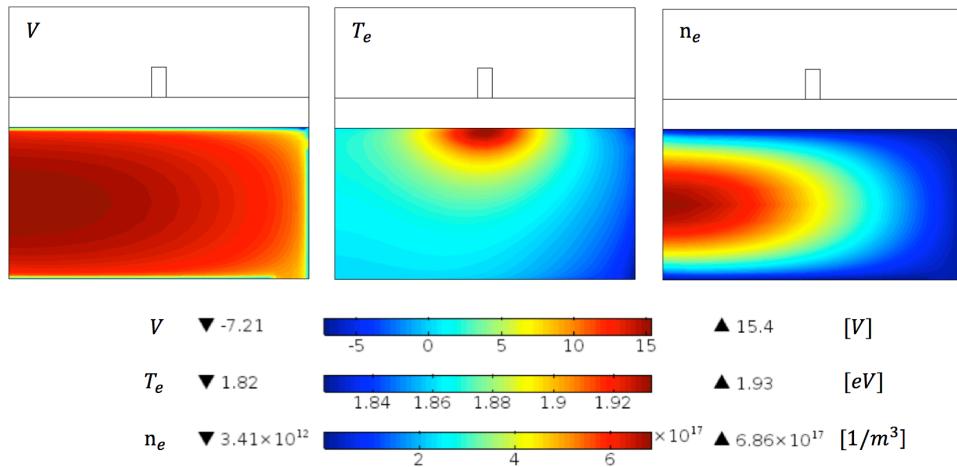
The electric potential was calculated by Poisson's equation as

$$\nabla^2 V = -\frac{e}{\epsilon_0} (n_i - n_e), \quad (8)$$

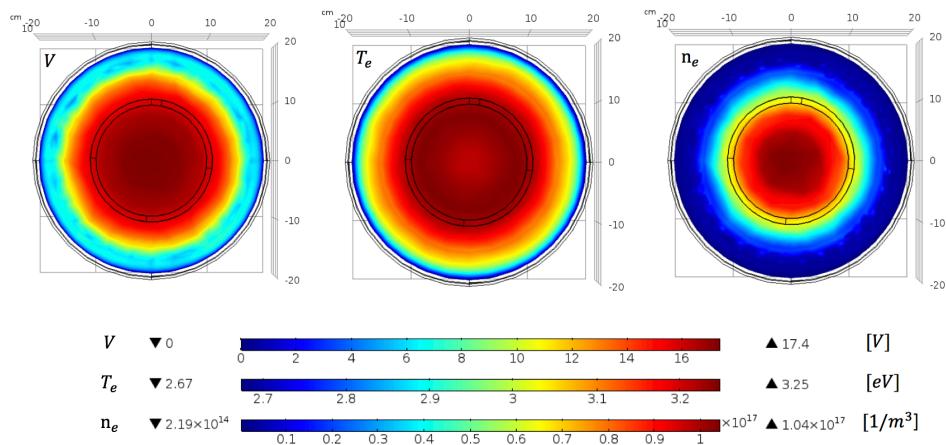
where  $\epsilon_0$  is the permittivity of vacuum.

### 3. Results and discussion

The symmetrical ICP discharge simulation is conducted, and the ICP discharge which has asymmetrical structure in terms of gas inlet is also simulated. The results are shown in Fig.2. and Fig.3, respectively. Fig.3 shows the sliced view of plasma chamber near the bottom surface (the coordinate:  $z = 1[\text{cm}]$ ). As the structure condition of gas inflow was varied, plasma properties such as electron density, electron temperature, etc. changed.



[ Figure 2. Symmetric case : Voltage ( $V$ ), Electron Temperature ( $T_e$ ), Electron Density ( $n_e$ ) ]



[ Figure 3. Asymmetric case : Voltage ( $V$ ), Electron Temperature ( $T_e$ ), Electron Density ( $n_e$ ) ]

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