A two-dimensional study of the capacitively coupled plasma discharge considering the effects of multiphysics

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[Abstract]

Plasma simulation methods were used to analyze discharge characteristics including the flow and heat transfer of the gas in the capacitively coupled plasma discharge. In this study, two - dimensional axisymmetric structure was assumed, which is common in the semiconductor device processes. Laminar flow model was used to calculate flow, heat transfer was considered to determine the temperature of the gas. Fluid description of plasma model was combined with flow and heat transfer models. Also, electron energy distribution function (EEDF) was obtained using two - term Boltzmann approximation. The plasma region was divided multiple zones, to consider the spatial variation of EEDF. Standing wave effect in the plasma discharge was added to investigate the electromagnetic field effect according to process conditions and driving frequencies.

Keywords: Plasma simulation, CCP discharge, Standing wave

1. Introduction

In this study, two-dimensional axisymmetric capacitively coupled plasma (CCP) discharge simulation was investigated including gas flow and heat transfer. This work was focused on the effect of driving frequency. According to the use of the larger electrode size and the high frequency source, the standing wave effect became important because of its nonuniformity problem. [1] It is well-known that, by changing the driving frequency, the electron density profile and non-uniformity are changed. To observe and analyze these, electromagnetic effects were considered. In this report, COMSOL Multiphysics was used for the simulations to include physical components.

2. Model description

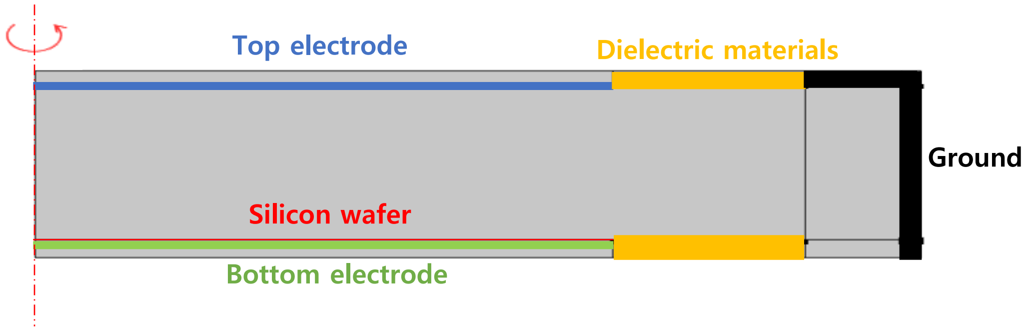

Figure 1. The schematic diagram of the CCP in this work.

In this simulation, the 2-Dimensional axial symmetric Capacitively coupled plasma model is used shown in Figure 1. The electrode length is 15 cm, and the radius of chamber is 22.5 cm. In actual semiconductor process, there is the thickness between air and chamber where the plasma generated so that designated as 0.5 cm with Aluminum. A 25 MHz with 30 V sinusoidal voltage is applied to above the top electrode and the bottom electrode is grounded. The gap between the powered and grounded electrodes is 5 cm. Silicon wafer is located on grounded electrode with the height of 0.075 cm, and there are dielectric materials(Al2O3) right next to electrodes, and side of the wall is grounded. For plasma discharge, Argon gas is used at 250 mTorr and reactions are shown in Table 1. In flow, the top electrode is set to inlet and the boundary of outlet is same with outflow in heat transfer in fluid physics.

No.	Process	Formula	Energy loss[V]
1	Elastic collision	$e + Ar \Rightarrow e + Ar$	
2	Ground state excitation	$e + Ar \Rightarrow e + Ar^*$	11.5
3	Super elastic collisions	$e + Ar^* \Rightarrow e + Ar$	-11.5
4	Ground state ionization	$e + Ar \Rightarrow 2e + Ar^+$	15.8
5	Step-Wise ionization	$e + Ar^* \Rightarrow 2e + Ar^+$	4.427

Table 1. Important collision processes in the argon discharge

The drift-diffusion approximation is adapted to describe electron and ion equations.

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma_e = (S-L)_e \qquad \Gamma_e = -n_e(\mu_e \cdot E) - D_e \nabla n_e$$

$$\frac{\partial n_i}{\partial t} + \nabla \cdot \Gamma_i = (S-L)_i \qquad \Gamma_i = -n_i(\mu_i \cdot E) - D_i \nabla n_i$$

$$\frac{\partial}{\partial t}\left(\frac{3}{2} n_e T_e\right) + \nabla \cdot \left(\frac{5}{2}\Gamma_e T_e - \frac{5}{2}\frac{e n_e T_e}{m_e \nu_{eN}} \nabla T_e\right) - e\nabla V \cdot \Gamma_e + P_{e,loss} = 0$$

$$\nabla^2 V = -\frac{e}{\varepsilon_0}(Z_i n_i - n_e)$$

Where n_e, Γ_e, $(S-L)_e$, μ_e, D_e, E, T_e, V, υ_{eN}, m_e, $P_{e,loss}$ are electron density, electron flux, source of electron and loss of electron, electron mobility, electron diffusivity, electric field, electron temperature, electric potential, collision frequency between electrons and neutral particles, electron mass, energy exchange during the collisional processes. And n_i, Γ_i, $(S-L)_i$, μ_i, D_i are ion density, ion flux, source of ion and loss of ion, ion mobility, ion diffusivity. Electric potential is calculated by Poisson equation and ε_0 is the permittivity of vacuum, Z_i is the relative charge on an ion.

The flow is calculated by using laminar module.

$$\rho\frac{\partial u}{\partial t} + \rho(u \cdot \nabla)u = \nabla \cdot \left[-pI + \mu(\nabla u + (\nabla u)^T) - \frac{2}{3}\mu(\nabla \cdot u)I\right] + F$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

Where u, I, F, ρ are average velocity, electrical current, force, volume charge density.

3. Results and conclusion

Time averaged simulation results are shown in Figure 2. In the simulation, for the source, Frequency = 100MHz, V = 100V are used at pressure = 250 mTorr. Between the electrodes, the electron density seems higher than near the ground wall. On the contrary, the electron temperature near the ground wall is high where the electron density is low. The electric potential shows similar aspect with electron density which showed highest value at the center of the two electrodes.

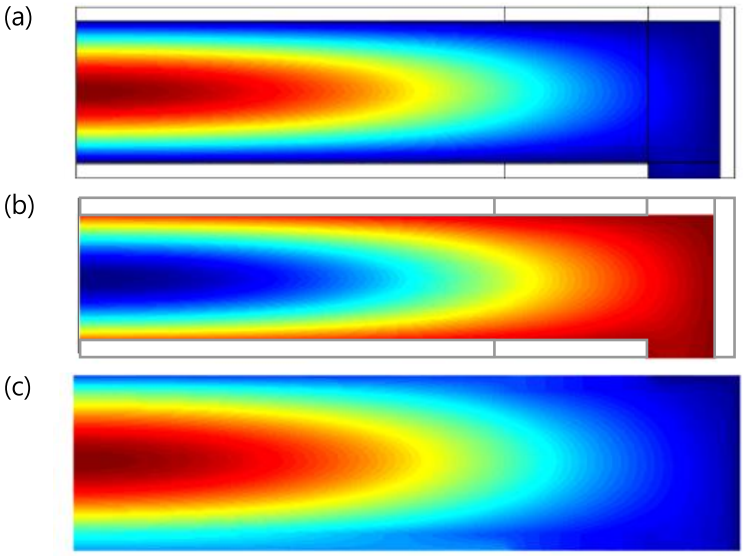

Figure 2. (a) the time-averaged electron density [m−3]; (b) the time-averaged electron temperature [V]; (c) the time-averaged electric potential [V]

Acknowledgement

This research was supported by the National Research Council of Science & Technology(NST) grant by the Korea government (MSIP) (No. CAP-17-02-NFRI).

References

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