Finite Element Analysis of Plasma Discharge and Sheath Characterization in Dry Etching Reactor

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Abstract **—This paper presents a full finite element analysis for plasma discharge in etching process of semiconductor circuit. The charge transport equations of hydrodynamic diffusion-drift models and the electric field equation are numerically solved in a fully coupled system by using a standard finite element procedure for transient analysis. The proposed method is applied to a real plasma reactor in order to characterize the plasma sheath that is closely related to the yield of the etching process. The base electrode of the reactor is modified to improve the edge effect for the uniformity. The experiment and numerical results are examined along with SEM data of etching quality. The feasibility and usefulness of the proposed method is shown by both numerical and experimental results.**

I. INTRODUCTION

Plasma etching and deposition is currently in widespread use in the manufacturing process of semiconductor circuit. However, despite of the importance of plasma processing, gas glow discharge is not well understood. This comes from the non-equilibrium nature of the plasma, and the complex interaction among potential field, transport phenomena, plasma chemistry, and surface reaction kinetics. So design of plasma reactor is still based largely on empirical approaches. Main requirements of plasma etching include high etching rate, uniformity, anisotropy, and selectivity. However, it is very difficult to satisfy all of the above requirements simultaneously. In addition, as the wafer size continues to increase, it becomes more difficult to satisfy uniformity and anistropy.

Recently, there has been increasing interest in developing mathematical models and numerical analysis of the plasma process in an effort to better understand the process and to improve the design of plasma reactors. The most frequently used algorithms are method of characteristics, flux-corrected-transport(FCT) method and particle-in-cell(PIC) method. The above algorithms are so complex for numerical implementation that extra delicate techniques are required. In addition, they cost long computation time and sometimes cause numerical instability [1]-[4].

In this paper, we propose a full finite element approach where the charge transport equations of hydrodynamic diffusion-drift models and the electric field equation are numerically solved in a fully coupled system by using a standard finite element procedure for transient analysis. The proposed method is applied to a real plasma reactor in order to characterize the plasma sheath just above a targeted silicon wafer. The plasma sheath is closely related to the yield of the etching process since it accelerates the bombing ions, whose motional properties determine the etching quality such as uniformity and anisotropy. Also, in this work the base electrode of the initial reactor is modified to improve the edge effect deteriorating the uniformity, and its experiment results of etching quality are compared with ones of the initial one by examining data of SEM(scanning electron microscope). That is, the feasibility and usefulness of the proposed method is shown by both numerical and experimental results.

II. ANALYSIS MODEL OF DRY ETCHING CHAMBER

Fig. 1 shows a cross-sectional diagram of the chamber for dry etching process. A wafer is placed between two electrodes. The upper electrode is connected to a voltage source and the lower one is set as ground. The electrodes supply external energy into the chamber for generating and sustaining the plasma. The electric field between the electrodes is downward and drives charge carries. The plasma sheath is formed just above the wafer and it accelerates heavy irons that bomb the wafer surface for etching. But the electric field above the wafer is not uniform in intensity and direction because of the fringing effect on the edge side. In this work, the uniformity of electric field is improved by substituting an existing quartz ring, which is located below the wafer, with an aluminum ring.

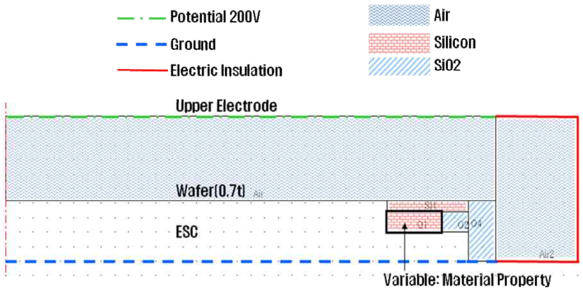


Fig. 1. Axis-symmetric geometry of dry etching chamber and design variables.

III. HYDRODYNAMIC DIFFUSION-DRIFT MODELS OF DISCHARGE

To analyze the phenomena of plasma discharge, hydrodynamic diffusion-drift models are employed. Three governing equations coupled with Poisson's equation are solved simultaneously for the concentration of the electron(N_e), positive(N_p) and neutral (N_n) with respect to time [5], [6]. The equations are as follow,

$$\begin{aligned}
&\frac{\partial N_e}{\partial t} + \nabla(N_e V_e) = S + N_n \alpha |V_e| - N_e N_p \beta_{ep} \\
&\frac{\partial N_p}{\partial t} + \nabla(N_p V_p) = S + N_n \alpha |V_e| - N_e N_p \beta_{ep} \qquad (1) \\
&\frac{\partial N_n}{\partial t} + \nabla(N_n V_n) = S - N_n \alpha |V_e| + \gamma
\end{aligned}$$

where, V_e, V_p and V_n denotes the electron, positive and neutral ion drift velocities and α and β denotes the ionization and recombination coefficients, γ denotes the concentration of new supplied gas. S denotes the source term.

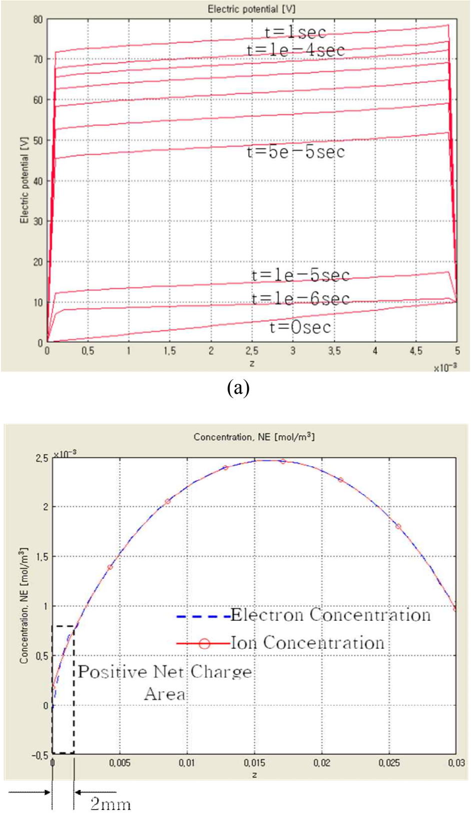
The electric field is calculated using Poisson's equation with the net charge of electron and ion.

$$\nabla(-\varepsilon \nabla V) = e(N_p - N_e) \qquad (2)$$

where, ε is electric permittivity, e is the quantity of electric charge and V is the electric scalar potential.

IV. NUMERICAL AND EXPERIMENTAL RESULTS

The discharge phenomena in chamber are modeled with the three transport equations coupled with Poisson's equation and they are calculated using the axisymmetric 3D finite element analysis. In Fig. 2(a) the electric potential along a z-direction is almost constant in the middle of two electrodes, meaning that plasma is neutral. A sheath region above the wafer is shown in Fig. 2(b).

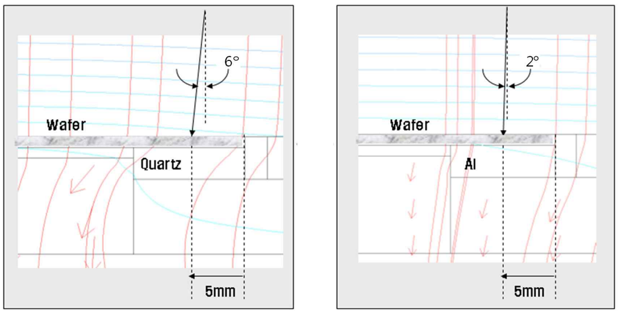


(a)

(b)

Fig. 2. Variation of (a) electric potential and (b) electron/ion density along the z-direction

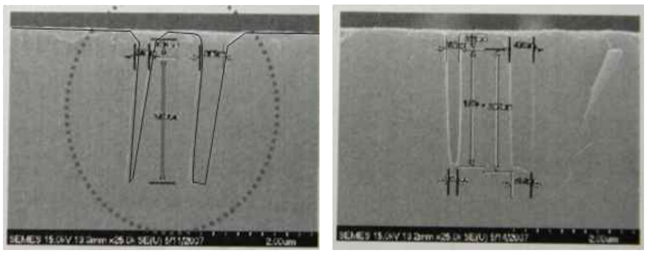
From the field analysis of plasma chamber, the uniformity of electric field near wafer edge is improved as shown Fig. 3(b). It means that an incidence angle of ion to the wafer etching target is more perpendicular compared with Fig. 3(a).



(a) (b)

Fig. 3. Comparison of electric field distributions when the Q1 block is (a) quartz and (b) aluminum ring

Fig. 4(a) shows the SEM image of the cross section near the wafer edge after dry etching is performed. The trench near the edge is not perpendicular to wafer surface because of the fringing effect of electric field near the wafer edge. By substituting the quartz block with a aluminum one, the tilt angle of trench is improved as shown in Fig. 4(b).



(a) (b)

Fig. 4. SEM images of wafer trench in (a) the existing quartz block and (b) the improved aluminum block.

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