Integrated Simulation of Equipment and Topography for Plasma Etching in the DRM Reactor

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Abstract - **An integrated procedure including the plasma equipment and profile modeling is developed and applied to the contact etching process for the DRM (Dipole Ring Magnet) reactor. In this simulation scheme, the static magnetic field solver, HPEM (Hybrid Plasma Equipment Model) and the topography simulator based on the level-set algorithm are used one by one to reproduce etch rates and profiles in terms of the equipment operating parameters such as the gas composition ratio and power. We investigated the contact etching of SiO_2 and Si_3N_4 in the DRM plasma reactor with $CHF_3/CO/O_2$ gas mixture. In case of etch rates at the wafer center, the results show agreement with the experimental values with less than 6% errors. The uniformities of the etch rate and contact profile also agree with those of experiments. These agreements show the possibility of the systematic simulation method in developing and optimizing a dry etching process.**

I. INTRODUCTION

The dry etching technology for the fabrication of ultra large scale integrated devices needs a precise control over the plasma equipment to meet the critical requirements such as uniformity, selectivity, and anisotropy. Thus, setting up a process for mass production becomes more and more costly in terms of time and money. The possibility to reduce the number of experimental trials using computer simulation has been challenged by many research groups [1,2]. The difficulty of process development demands the understanding of the surface reaction and plasma process phenomena; thus, the plasma modeling and simulation become increasingly important. In the similar context, a simulation flow that can systematically maintain the information flow from equipment simulation to topography simulation is newly developed for the DRM plasma reactor.

The DRM reactor is a MERIE (Magnetically Enhanced Reactive Ion Etcher) type and extensively used in the contact etching process, which is mostly the silicon oxide etching process, but has some problems such as etch stop and RIE-lag. The DRM reactor has a very complicated magnet structure around the reaction chamber, which rotates in tens of rpm to improve the uniformity. This magnet structure adds another dimension in complexity for plasma simulation. For this reason, plasma equipment simulation for DRM has not been studied up to now.

The integrated simulation flow links a plasma equipment model with a static magnetic field solver, the RF sheath model, and the feature scale profile model [3]. The plasma equipment model is based on the HPEM [4] and the magnetic field is solved using FEM(Finite Element Method) based VectorFields to accurately take account the magnetic fields arising from the rotating magnets. The unified RF plasma sheath model that is known to cover the full spectrum from resistive to capacitive sheath limits is used [5]. In addition, the etch profile the evolution is calculated by the in-house simulator based on level-set algorithm [6].

This integrated simulation scheme is applied to the contact etching of SiO_2 under the $CHF_3/CO/O_2$ plasma and the influence of the gas composition ratio and power is investigated.

II. THE SIMULATION FLOW AND ETCH MODEL

A. Flow of Integrated Simulation

Fig.1 shows the schematic of the integrated simulation flow from the plasma equipment to topography. First, the magnetic fields induced by the complex permanent magnets of the DRM equipment are 3-dimensionally computed using a commercial software, VectorFields. The calculated static magnetic showed a good agreement with the measured values and distributions.

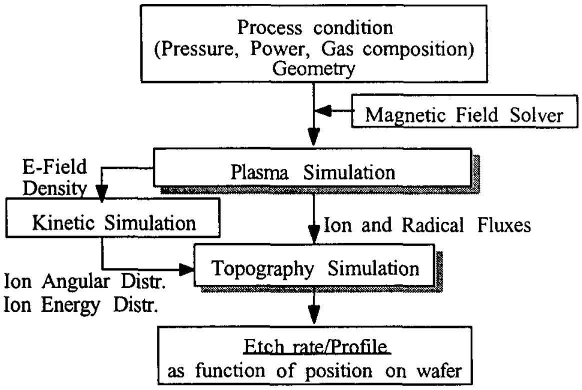

Fig. 1. The proposed integrated plasma simulation flow.

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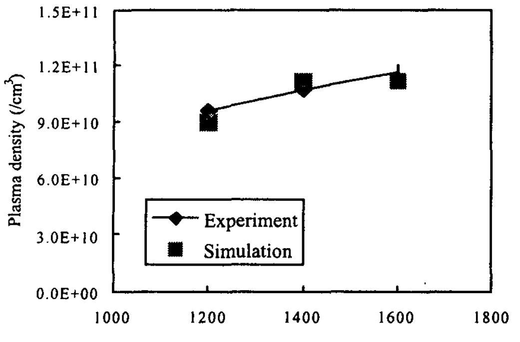


Fig. 2. Comparison of the plasma densities between simulation and experiment in the chamber centerline for an Ar discharge of 40mT and 200 sccm at three different powers.

The plasma parameters are computed at several 2-dimensional cross-sections with a distinctive magnetic field distribution and overall etching characteristics are obtained by averaging over these several 2-D calculations. This DRM equipment simulation flow was validated by comparing the calculated Ar plasma density with the measured data, as shown in Fig. 2.

The equipment simulation produces the density and flux distribution of ions and radicals incident onto the wafer as a function of the radial position. Subsequently, the energy and angular distributions for all particles striking the wafer are obtained using a Monte Carlo simulation including a sheath model. Then, the feature scale topography simulations are performed using these results obtained by the plasma equipment model. Therefore, the uniformity of the etch rate and profile evolution are obtained in terms of plasma process conditions.

B. Surface Etch Model

The surface reaction equations used in the topography simulation are given as

$$R_d = k_d(S_c F_r - Y(\theta) F_i) \quad (1)$$

$$R_e = k_e F_{eff}/(1+F_{eff}/S_c F_r) \quad (2)$$

where R_d is the deposition rate of polymer and R_e is the etch rate of the silicon oxide layer. k_d, k_e, S_c, and $Y(\theta)$ denote the deposition rate constant, the etching rate constant, the reactive sticking coefficient of radical, and the sputter yield function, respectively. F_r and F_i are the radical flux and the ion flux onto the wafer surface, respectively, which are calculated from the plasma equipment simulation. These fluxes are modified considering the re-emission of the radical and the reflection of the ion in the feature level. F_{eff} is $F_i - F_t$, where F_t $(=S_c F_r/Y(\theta))$ is the threshold ion flux when the polymer deposition rate is zero.

When the total incident flux is fixed, Fig. 3 shows the etch rate as a function of the ratio of ion to radical flux. When the ratio is very low, the polymer is deposited. As the ratio of ion to radical flux increases, the ion flux limited regime is converted into the radical flux limited regime, and the etch rate has the maximum value. If the aspect ratio of the contact increases, the ratio of ion to radical flux increases. Therefore, this etch model can explain the loading effects such as the RIE-lag that the etch rate increases with the contact diameter, reverse RIE-lag, and polymer deposition.

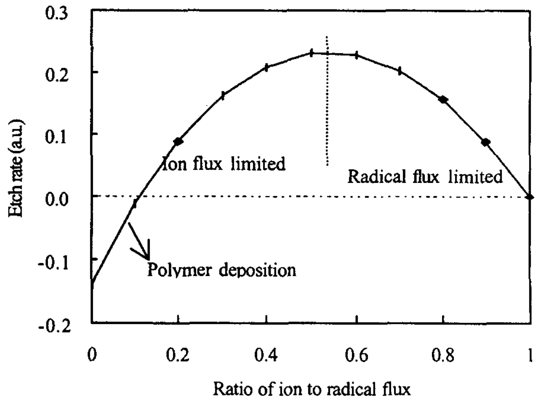


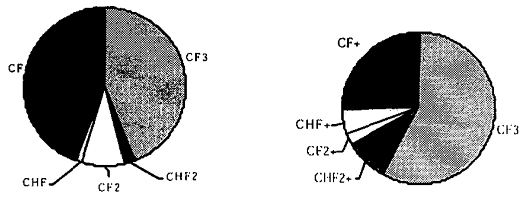
Fig. 3. Etch rate as a function of the ratio of ion to radical flux.

III. RESULTS OF PLASMA AND PROFILE SIMULATIONS

A. DRM Plasma Characteristics of $CHF_3/CO/O_2$ Mixture

Plasma equipment simulations for $CHF_3/CO/O_2$ mixture in the DRM reactor were performed. The cycle-averaged plasma density is an order of $10^{10}/cm^3$ and the electron temperature is about 2 eV.

Fig. 4 shows the relative flux distribution of ions and radicals incident onto the wafer. In case of radical flux, CF_3 and CF are the major fluorocarbon species on the wafer and CF_2 radical is relatively small. In case of ion flux, the results show that CF_3^+ and CF+ are also dominant ion species and CHF_2^+ occupies relatively larger portion in the total flux compared to that in the radical flux. Fig. 5 shows the ion and radical flux as a function of the radial position on the wafer. The distribution of radical flux is nearly uniform, but the ion flux tends to increases in the radial direction in some cases.



(a) (b)

Fig. 4. The relative flux distribution of (a) radicals and (b) ions incident on to the wafer.

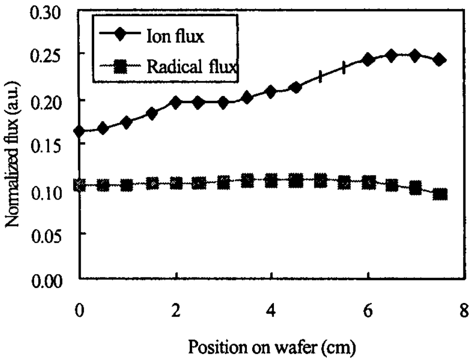


Fig. 5. The radial distribution of radical and ion flux incident on to the wafer.

The ions collide perpendicularly against the substrate with less than the incident angle of 5°, and the angular distribution is nearly independent on the process condition. The ion energy distribution has the double peaks, which is a general characteristic of the RF capacitively coupled plasma.

B. Effect of Process Condition on the Etch Rate

The etch rates of silicon oxide and nitride at the wafer center were calculated for the gas composition ratio and power at the pressure of 35mTorr. As demonstrated in Table I, the etch rate increases with the fraction of CHF_3, which is due to the increase of the radical flux. The change of power leads the similar trend and in this case the ion and radical flux increases together as the power increases. Using the same etch model equation, the calculated etch rates of both silicon oxide and silicon nitride show a good agreement with experimental data with less than 6% errors.

Fig. 6 shows the measured and calculated etch rates of silicon oxide and silicon nitride in the radial direction on a non-patterned wafer in terms of the gas composition ratio. Simulation results show the same tendency with experiments and reproduce the well known characteristic feature that the etch rate has a maximum value near the edge of wafer.

The etch rates of the silicon oxide in the patterned wafer with a contact diameter of 250 nm and a mask thickness of 700 nm were calculated in terms of the gas composition ratio and the position on the wafer using the same etch model of the non-patterned wafer. The results are shown with those of the non-patterned wafer in Fig. 7. The measured data show that the etch rate is high in the patterned wafer and also the difference in the etch rate between at the wafer center and edge is above twice, compared to that of the non-patterned wafer. The simulation results show a good agreement with these experimental trends.

TABLE I

ETCH RATES OF SILICON OXIDE AND NITRIDE ON THE CENTER OF THE NON-PATTERNED WAFERS AT THE PRESSURE OF 35 mTorr

Process ($CHF_3/CO/O_2$)	Etch Rate (A/min)					
	SiO_2			Si_3N_4		
	Sim.	Exp	Error(%)	Sim.	Exp.	Error(%)
1500 W/31/150/10	2117	2019	4.87	1850	1836	0.78
1500W/35/150/6	2454	2560	-4.18	2133	2036	4.72
1500W/39/150/2	2755	2737	0.65	2362	2262	4.39
1200W/35/150/6	2156	2294	-6.02	1846	1924	-4.04
1800W/35/150/6	2665	2726	-2.23	2314	2191	5.60

B. Effect of Process Condition on the Etch Profile

Using the ion and radical fluxes obtained from the plasma equipment simulation, profile simulations were performed for SiO_2 contact etch process at several positions on the wafer. The calculated etch profiles on the wafer center and the edge are shown with the SEM photographs in Fig. 8. As shown in the figures, the integrated simulation flow reproduces the change of the contact profile slope very well.

The etch rate increases as the fraction of CHF_3 increases as explained in the previous section, but the side wall slope increases. Thus, there seems to be the optimum gas composition ratio. The increase of the side wall slope results from the increase of the radical flux with the fraction of CHF_3, which is explained well by the integrated simulation scheme.

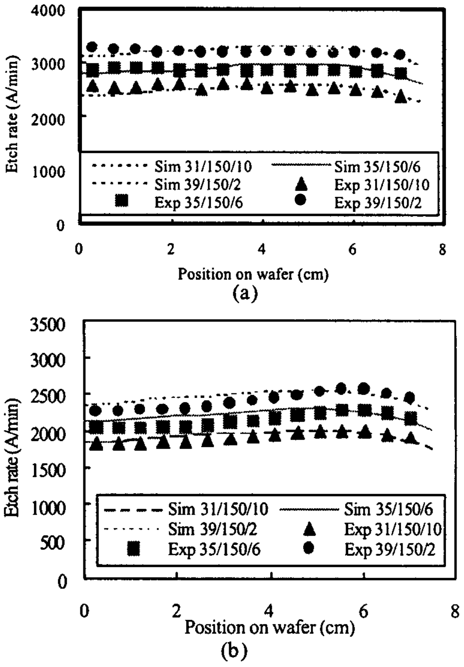
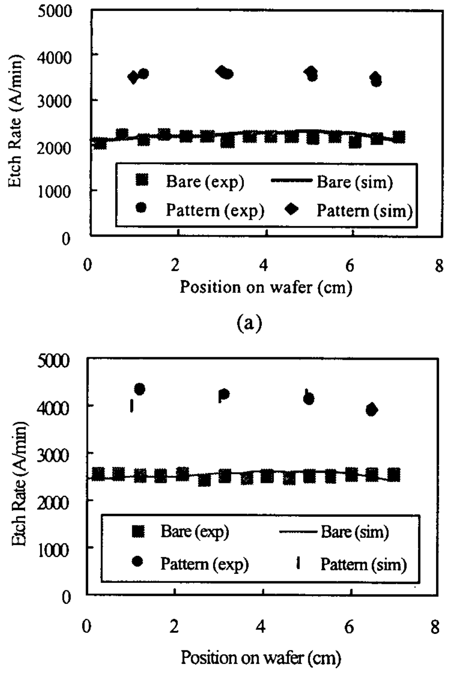


Fig. 6. Etch rate distributions of (a) silicon oxide and (b) nitride on the non-patterned wafers at 35 mTorr and 1500W.



(a)

(b)

Fig. 7. Etch rate distributions of silicon oxide on the non-patterned wafers at (a) 31/CHF$_3$/150CO/10O$_2$ and 35CHF$_3$/150CO/6O$_2$.

IV. CONCLUSIONS

We developed a simulation procedure in which the plasma equipment and profile model are integrated to produce the etching properties in terms of equipment operating conditions in the DRM reactor. This scheme was applied to the contact etching process using the CHF$_3$/CO/O$_2$ gas mixture to investigate the effect of the process conditions on etch rate distributions and contact profiles. The etch rates of SiO$_2$ and Si$_3$N$_4$ were modeled well with less than 6% errors as a function of the gas composition ratio and power. In addition, the calculated results such as the etch rate distribution and contact profile agreed well with experimental data. Therefore, it is expected that this simulation scheme can be effectively used in optimizing and developing the dry etching process.

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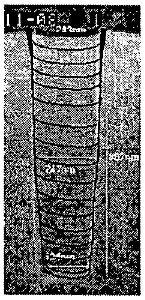
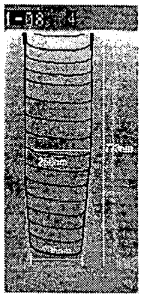
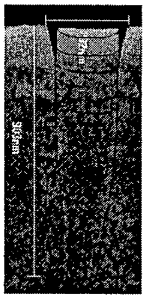
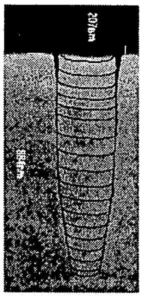
Gas Ratio (CHF$_3$/CO/O$_2$)	Center	Edge
35/150/6		
39/150/2		

Fig. 8. Comparison between simulated (lines) and SEM's of the SiO$_2$ etch profile.

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