Plasma etching and feature evolution of organic low-k material by using VicAddress

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Abstract

Plasma process is a highly selective technique exploiting the individual or mixed function of positive ions, electrons, neutral radicals, and photons produced by low temperature plasmas. For example, dielectric etching is a competitive process among charging, etching and deposition at each of local positions of a geometrical structure exposed to reactive plasmas. Plasma etching is adjacent to the damage, such as charging, thermal heating, and UV-irradiation, caused by these elements. VicAddress (Vertically integrated computer aided design for device processes) developed in our laboratory has a threefold frame, including two-dimensional (2D) plasma structure, particle sheath kinetics, and particle-wafer interaction, in the multi-scale system of the plasma process. We will discuss the numerical procedure of a plasma surface interaction for etching. Time-averaged 2D plasma in a two-frequency capacitively coupled plasma reactor of several cm in dimension is connected to the wafer surface having a pattern of a size of sub-micron. The influence of deposition on etching of organic low-k is numerically discussed in terms of the feature profile evolution.

Key words: Plasma etching, Feature profile, competitive process between etching and deposition

1. Introduction

State-of-the-art technology of semiconductor device fabrications enters upon a phase of physics-based design for the plasma etching of contact holes and interconnect holes/trenches on dielectrics in addition to the gate metals in ultra large-scale-integrated (ULSI) circuits. The design of plasma processes will differes from that of a traditional TCAD (Technology Computer Aided Design) for device operation in the point that the objective surface changes in space and time, influenced by the reactive plasma property of feed gas molecules.

We have developed a prototyped CAD called VicAddress (Vertically Integrated Computer Aided Design for Device pRocESSes) including a structure of plasma sources and surface processes by considering damage

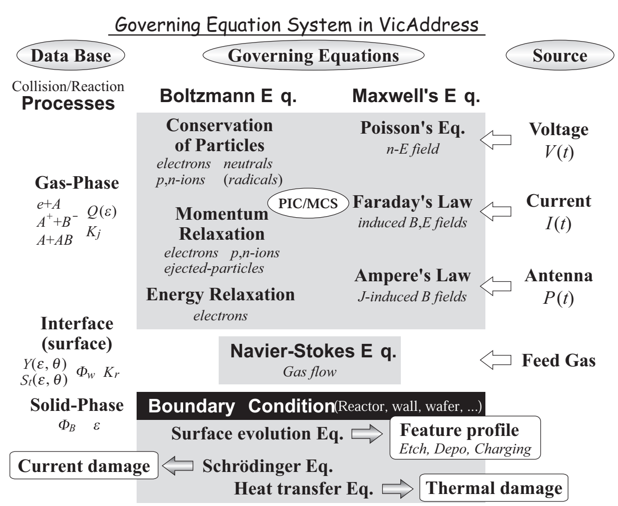

Fig. 1. Schematics of VicAddress.

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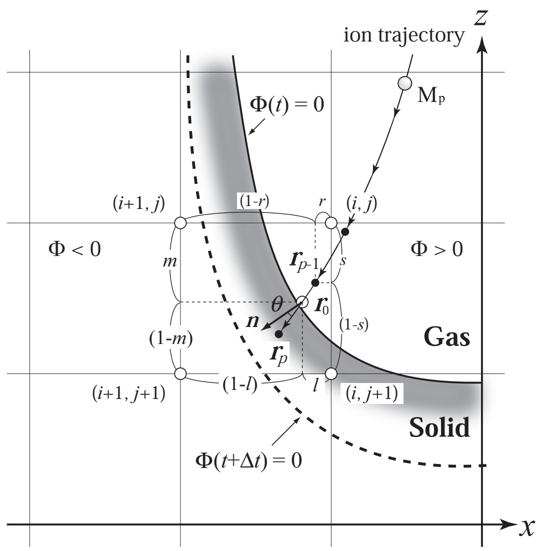

Fig. 2. Schematic diagram of Level-set method and surface evolution.

of lower level device elements [1]. In the present study, we discuss a dielectric etching under competitive processes between deposition and etching. In practical etching, the wafer exposed to reactive plasmas has a plurallayer interface structure, owing to a surface modification by or deposition of active species incident on the surface. These phenomena have been actually found in SiO_2 etching, and the wafer surface is changed from a pure SiO_2 to a interfacial CF-polymer layer with a lower mixing layer consisting of Si, O_x, and F_y [2]. In addition, the dielectric wafer is charged and the potential of the inside of the hole or trench will be locally distributed [3]. As a result, the surface process is a competition among charging, deposition, and etching, and the feature profile evolution is estimated under these competition by level-set method [4,5].

In this paper we describe a numerical procedure of a feature profile evolution by plasma etching of organic low-k material (FLARE) affected to a considerable degree by deposition. In the case of the reactive ion etching (RIE) of the organic low-k exposed to plasma in N_2/H_2, we have to consider neutral radicals and ions as active species for etching and deposition. One is H radical which spontaneously etches the low-k material followed by a release of gaseous CH_j. Another is N radical which forms a CN-polymer layer. The others are energetic ions, mainly H_2^+ and N_2^+ which have their ability to etch the low-k material and CN polymer film .

The plasma etching is achieved practically after a finite time of aging which provides the quasiequilibrium condition of the surface coverage θ_{B_s} on the wall, $\sum_B \theta_{B_s}$ =1. We here consider the reactions of the neutrals, H, N, NH, NH_2, and NH_3 incident on the wall. Then the spatiotemporal change of N_s, H_s, NH_s, NH_{2s}, and NH_{3s} on the surface is expressed by the site balance equation [6]. It means that the surface of the organic low-k, exposed to the plasma in N_2/H_2, will be modeled by considering a two-layer structure consisting of a top CN-polymer film and underlying organic low-k material (see Fig. 3).

2. Method

The effective etching rate $R_E(\boldsymbol{r}, t)$ at $\boldsymbol{r}$ and t on the surface will be expressed in terms of the etching rates of CH_x- and CN-layers, $R_{E(CH_x)}$ and $R_{E(CN)}$, and the deposition rate of CN-layer, $R_{D(CN)}$ as

$$R_E(\boldsymbol{r}, t) = R_{E(CH_x)}(\boldsymbol{r}, t) + R_{E(CN)}(\boldsymbol{r}, t) - R_{D(CN)}(\boldsymbol{r}, t) \quad (1)$$

In a time-evolution of the surface during Δt, two cases arise from the competition between etching and deposition as shown in Fig. 4. That is,

(a) $R_{E(CN)}\Delta t \ < \ L_{depo} + R_{D(CN)}\Delta t$

During etching, the organic low-k is always covered by previously deposited-CN layer, L_{depo}, and simultaneous deposition $R_{D(CN)}\Delta t$. The etching and deposition rates of each of layers are given

$$R_{D(CN)} = \frac{1}{\rho_{CN}} S_{t(N)} \Gamma_N, \quad (2)$$
$$R_{E(CN)} = \left(\frac{L_{poly}}{\Delta t} \right)$$

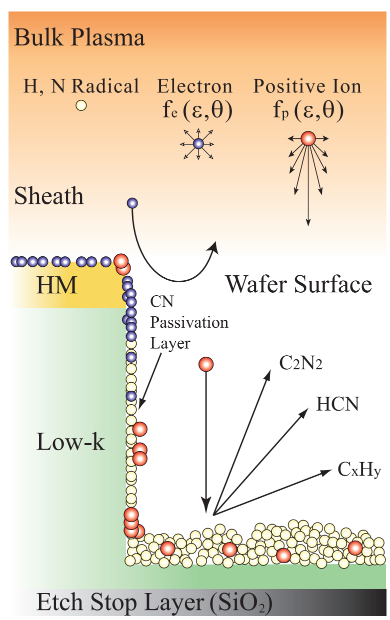

Fig. 3. Schematic diagram of organic low-k etching by RIE in N_2/H_2.

$$= \frac{1}{\rho_{CN}} \sum_k \int_\theta \int_\epsilon Y_{CN_k}(\epsilon,\theta) f_{p_k}(\epsilon,\theta) d\epsilon d\theta, \quad (3)$$

$$R_{E(CH_x)} = 0, \quad (4)$$

where $S_{t(N)}$ and Γ_N is the surface sticking coefficient and flux of neutral N radicals incident on the surface. ρ_{CN} is the number density of CN layer. $f_{p_k}(\epsilon,\theta)$ is the flux velocity distribution of H_2^+ and N_2^+ ions incident on the surface, defined respectively as $\Gamma_{p_k}(\boldsymbol{r},t) = \int\int f_{p_k}(\epsilon,\theta,\boldsymbol{r},t) d\epsilon d\theta$. $Y_{CN_k}(\epsilon,\theta)$ is the etching yield of the ion.

(b) $R_{E(CN)}\Delta t \geqq L_{depo} + R_{D(CN)}\Delta t$
In this case lower organic low-k layer is etched during Δt, and each of rates is given

$$R_{D(CN)} = \frac{1}{\rho_{CN}} S_{t(N)} \Gamma_N, \quad (5)$$

$$R_{E(CN)} = \frac{1}{\rho_{CN}} \sum_j \int_\theta \int_\epsilon Y_{CN_j}(\epsilon,\theta) \frac{L_{depo}}{L_{poly}} f_{p_j}(\epsilon,\theta) d\epsilon d\theta, \quad (6)$$

$$R_{E(CH_x)} = \frac{1}{\rho_{CH_x}} \sum_j \int_\theta \int_\epsilon Y_{CHx_j}(\epsilon,\theta) \left(1 - \frac{L_{depo} + R_{D(CN)}\Delta t}{L_{poly}}\right) f_j(\epsilon,\theta) d\epsilon d\theta, \quad (7)$$

where $f_j(\epsilon,\theta,\boldsymbol{r},t)$ is the flux velocity distribution of H_2^+, N_2^+ ions and H radicals, respectively.

The sticking coefficients of H and N radicals on the low-k surface are taken to be 0.11 and 0.3, respectively. The surface evolution is described by a Hamilton-Jacobi type of equation, i.e., level-set equation,

$$\frac{\partial\Phi(\boldsymbol{r},t)}{\partial t} - R_E(\boldsymbol{r},t) \left|\frac{\partial\Phi(\boldsymbol{r},t)}{\partial \boldsymbol{r}}\right| = 0, \quad (8)$$

where $\Phi(\boldsymbol{r},t)$ is a level set function[7]. Two-dimensional space- and time-modulated plasma structure in the two-frequency capacitively coupled plasma (2f-CCP) is first computed [8]. In the sheath region in front of the biased-wafer, the velocity distribution of ions incident on the surface is simulated by MCS as functions of $\boldsymbol{r}$ and t by using the inner plasma parameters in real space. Under a selfconsistent procedure test ions with the above simulated flux velocity distribution and electrons are traced toward the trench structure, and the time evolution of the surface is stimated by Eq. (8).

3. Results

We investigate the influence of the mixture of N_2/H_2 on the trench profile at typical conditions of the low-k etching in the 2f-CCP reactor, driven by a VHF of 100 MHz and amplitude of 300 V, and biased by a LF of 1 MHz and 700 V at each of electrodes at 50 mTorr.

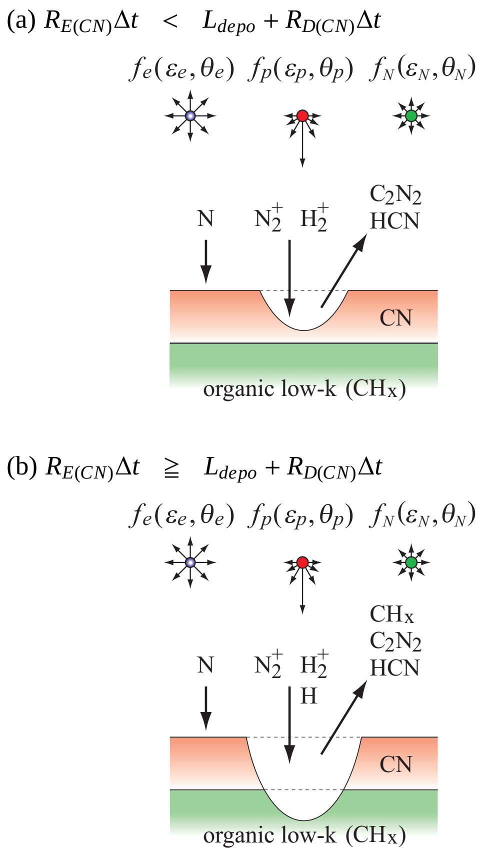

Fig. 4. Surface model of etching of organic low-k materials by H_2/N_2 plasma.

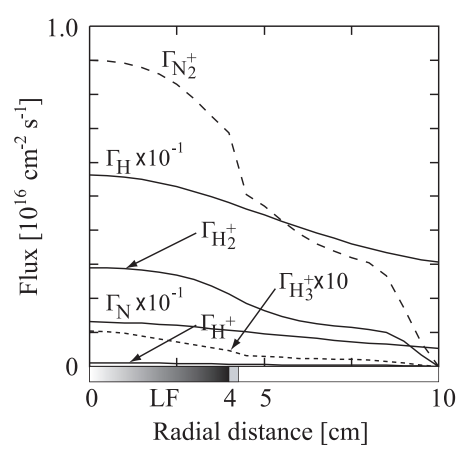

Fig. 5. Arrival flux of ions and radicals at biased organic low-k surface and earthed metallic plate. External conditions are 50 mTorr in N_2/H_2(50%) and 100 MHz and 300 V (plasma source) and 1 MHz and 700 V (bias source).

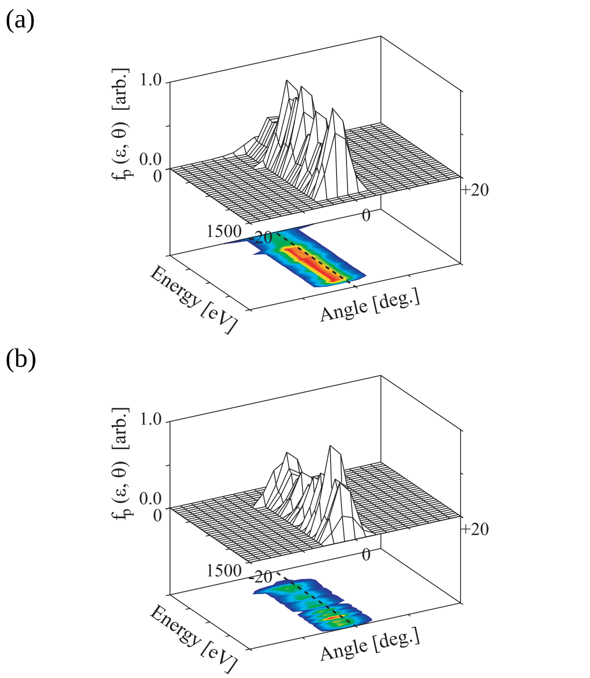

Fig. 6. Flux ion velocity distribution in N_2/H_2(75%). N_2^+(a) and H_2^+(b). Other external conditions are in the text.

6 charged and 36 neutral species are considered in the system. In the interconnect-dielectric etching, the aspect ratio of the trench or hole is low, and the effect of the local charging of the inside wall is not significant.

Figure 5 shows the flux distributions of active species incident on the wafer at N_2/H_2(50 %). Here the neutral flux of radicals is one order of magnitude greater than the ions. We will discuss the etching at the central part of the wafer where the incident flux is radially uniform. The flux velocity distribution of N_2^+ and H_2^+ ions incident on the biased wafer are shown in a time-averaged form in Fig. 6 at N_2/H_2(75%). The distributions of H_2^+ and N_2^+ have an incident angle of 5 degree at FWHM. Finally the temporal surface evolution is numerically obtained by using the level-set equation as shown in Figs. 7(a) - 7(d). We will find the change of the trench from a taper profile to bow as well as the increase of the etching rate, when only the percentage of H_2 increases at the same external conditions. The change of the shape is caused by the competition among the incident fluxes, H, N, H_2^+, and N_2^+.

Optimal external plasma conditions to perform a fine trench profile will be estimated from the series of modeling in VicAddress.

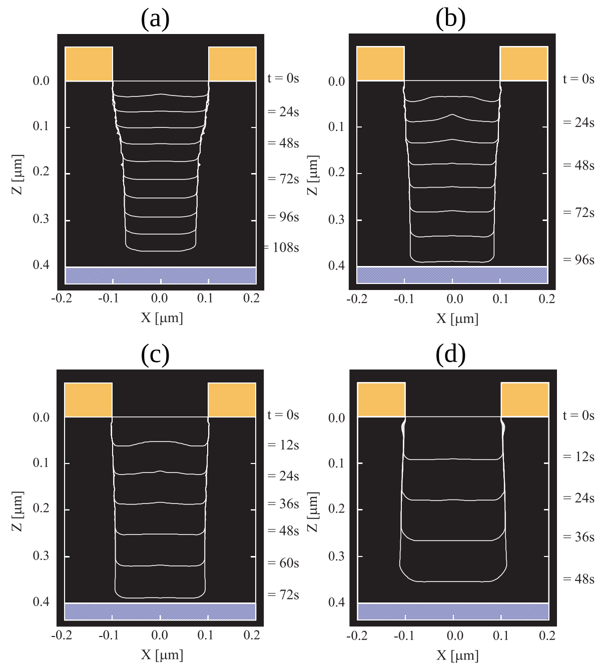

Fig. 7. Feature etching profile of organic low-k (FLARE) as a function of gas mixture. N_2/H_2(5%) (a), N_2/H_2(25%) (b), N_2/H_2(50%) (c), and N_2/H_2(75%) (d). Other external conditions are in the text.

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