

Feature Charging During Cryogenic Plasma Etching

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Abstract—Cryogenic plasma etching (CPE) of dielectrics using HF-based chemistry results in condensed acidic water layers many to tens nm thick on the surface of the dielectric. Results from simulations are discussed of the consequences of conductive water layers on charging of high aspect ratio SiO₂ features during CPE.

Keywords—cryogenic plasma etching, reactor- and feature simulations, feature charging, conductive layers

I. INTRODUCTION

Cryogenic plasma etching (CPE) is being developed to accelerate etching rates and improve critical dimension (CD) control in fabrication of high aspect ratio (HAR) features in dielectrics [1,2]. One such application is etching of vias through stacks of alternating layers of silicon dioxide and silicon nitride (ONO) for 3D-NAND memory in which aspect ratios approach 100 [3,4]. In CPE, the substrate is cooled to temperatures as low as -140 °C [1,5]. Adsorption probabilities of etch precursors generally increase with decreasing substrate temperature. Typical gas mixtures used for CPE of dielectrics include HF, which upon etching SiO₂ generates water as a product. Adsorption of the H₂O then produces a thin condensed water layer (a few to 10-20 nm) into which HF hydrolyzes to form an acidic environment similar to a liquid hydrofluoric acid etch [6]. Upon energetic ion bombardment of several keV, etch rates are hundreds of nm/minute [1].

During HAR plasma etching of dielectrics, the interior of features typically charge positively due to a disparity between the energy and angular distributions of ions and electron fluxes incident onto the wafer [7]. The intra-feature charging, up to 1 kV, slows the incoming positive ions and can deflect their trajectories, decreasing etch rates and initiating defects such as twisting. In plasma etching using fluorocarbon gas mixtures, the materials are generally non-conducting, which leads to large local electrical potentials. The conductive condensed layers encountered in CPE are able to spread the charging throughout the feature and counter the potential buildup by polarization of its intrinsic charge. The end result is a reduction in the local electrical potential while reducing the likelihood for charging to create defects.

II. DESCRIPTION OF THE MODELS

The reactor scale simulations were performed with the Hybrid Plasma Equipment Model (HPEM) [8,9]. Feature scale simulations were performed with the

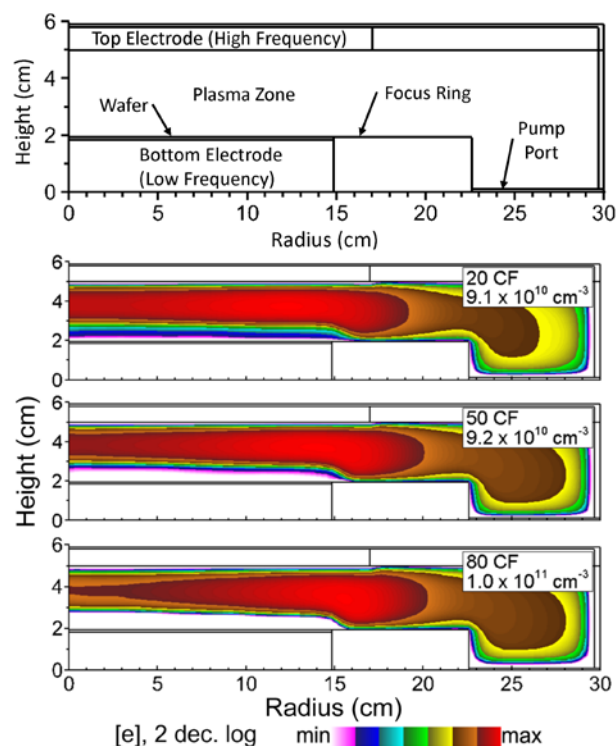


Figure 1 – (top) Dual-frequency capacitively coupled plasma (CCP) reactor with high frequency power applied to the top electrode and low frequency applied to the lower electrode. (bottom) Electron density for 2000 W bias power for CF = 20, 50 and 80.

Monte Carlo Feature Profile Model [10,11]. The electrical potential in the MCFPM is produced by solving Poisson's equation using the accumulated charge delivered to surfaces of the feature. Continuity equations for charge include current flow through materials. The acidic condensed layers contain H₃O⁺ cations and fluoride anions, whose drift motion polarizes the liquid in a similar manner as intrinsic charges in conductors. To account for the polarizing in-liquid species and charges delivered to surface by plasma generated species, the method of solving Poisson's equation for electrical potential was improved. The model separately tracks the transport of positive and negative intrinsic charge carriers within conducting materials (including the acid layer); and charge that originates by plasma delivered electrons and ions. Algorithms have also been added for desorption of adsorbed species; and their re-adsorption. This is a temperature dependent process that can extend transport of volatile species deeper into the feature.

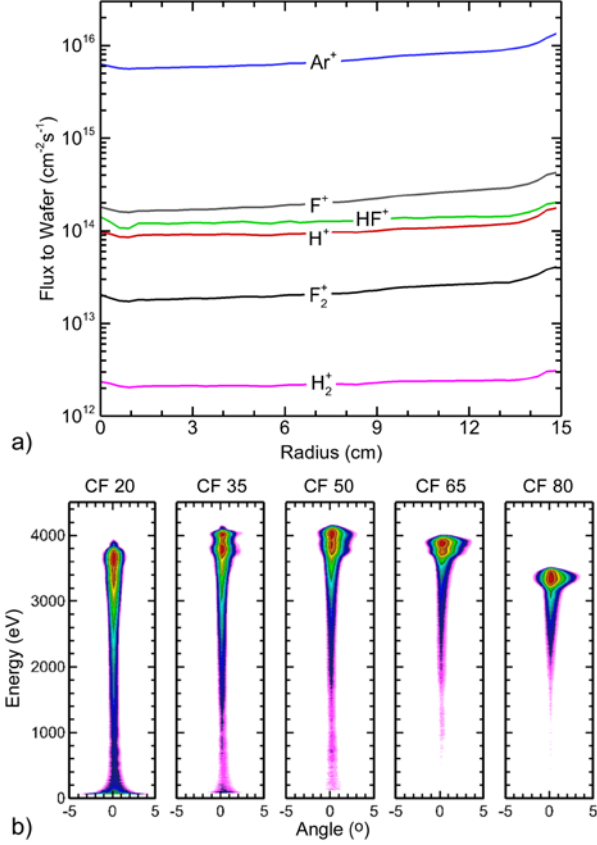


Figure 2 – Ion properties onto the wafer. a) Ion fluxes across the 30 cm diameter wafer. b) IEADs for a RB at 1 MHz with constant -4000 V amplitude for different CF.

The reaction mechanism employed in the MCPFM for HF-plasma based CPE of SiO₂ is discussed in Ref. [12]. The HF plasma chemistry reaction mechanism employed in the HPEM for Ar/HF gas mixtures is discussed in Ref. [13].

III. IN FEATURE CHARGING DURING CPE OF SiO₂

The reactor in this study modeled by the HPEM is a capacitively coupled plasma (CCP) sized for a 30 cm diameter wafer using a Ar/HF = 70/30 gas mixture at 40 mTorr. (See Fig. 1.) The gap between the wafer and upper electrode is 3.05 cm. The substrate is biased at 1 MHz. The upper electrode is biased at 40 MHz with a power of 500 W. The substrate temperature for the MCPFM is varied between +30 °C and -110 °C. The feature is a trench consisting of 3200 nm thick SiO₂ over a Si stop-layer with an amorphous-carbon mask 800 nm thick having an opening of 80 nm producing an aspect ratio of 40. The simulation is performed in 3-dimensions, with a finite depth of the trench of 40 nm using reflective boundary conditions. The mesh consists of cubic voxels 4 nm on a side. Water-acid layers have a conductivity of 0.47 S/cm while non-acidic water layers have conductivity of 0.23 mS/cm. (These conductivities are referred to as σ_0 .)

In HAR plasma etching, optimum feature properties are produced by ion fluxes onto the wafer that are high

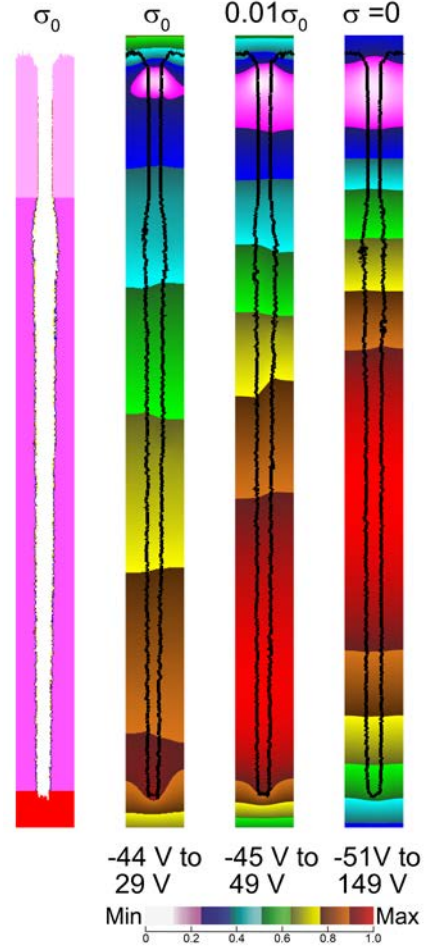


Figure 3 – Cryogenic plasma etching of SiO₂ in a CCP sustained in Ar/HF. (left) Feature profile after 20% over-etch. (right) Electric potentials (V) in the feature for full liquid conductivity σ_0 , $0.01\sigma_0$ and no conductivity.

energy, mono-energetic, and have narrow angular distributions. These properties can be achieved with substrate biases that use non-sinusoidal waveforms. One such waveform is the *rectangular-bias* (RB) in which, in square wave fashion, the bias is held at a constant negative voltage followed by a constant positive voltage. The percentage of the cycle the voltage is held negative and accelerates ions is the *cathodic fraction* (CF). Electron densities averaged over the RF cycle are shown in Fig. 1 for CF = 20, 50 and 80. Larger CF produces a thicker cycle-averaged sheath which diverts plasma density to larger radius, producing a slope in the sheath boundary. These sheath properties may result in angular tilt to the ion energy and angular distribution (IEAD) incident onto the wafer. The ion fluxes to the wafer (Fig. 2a) are dominated by Ar⁺ and not particularly sensitive to the CF of the bias. The IEADs to the wafer for constant voltage amplitude of -4000 V for CF = 20 to 80 % are shown in Fig. 2b. The IEADs are more monoenergetic with larger CF. Due to an increasingly positive DC bias, the maximum ion energy decreases at large CF.

The fully etched trench is shown in Fig. 3 for a substrate temperature of -70 °C, constant bias power of

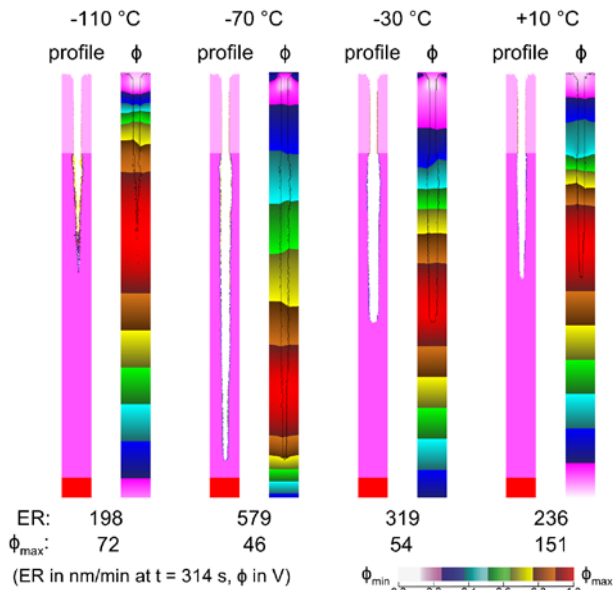


Figure 4 – Feature profile and electric potential for CPE of SiO₂ in a CCP sustained in Ar/HF for different substrate temperatures. ER = etch rate and ϕ = potential.

2000 W for a sinusoidal waveform. The bottom of the feature reaches the stop layer in 440 s producing an etch rate of 436 nm/min. The feature as shown in Fig. 3 is after a 20% over-etch to straighten the initially tapered sidewalls. The bowing CD is 136 nm, bottom CD 72 nm and taper CD is 64 nm. The dark coloring on the surface of the SiO₂ is the adsorbed water layers (acid and non-acid). When excluding conductivity of the water layers, the range of in-feature electric potential is -51 V at the top of the feature to 149 V at the middle of the feature. This maximum in potential is the location where positive ions are most likely to neutralize when striking the sidewalls and deposit positive charge. When allowing the water and acid layers to have conductivity, the maximum positive potential decreases to 49 V for a conductivity $\sigma = 0.01\sigma_0$ and to 29 V for $\sigma = \sigma_0$. When changing conductivity, the mobilities of charges are held constant; and so the change in conductivity corresponds to a change in intrinsic charge densities. With increasing conductivity the location of the maximum potential shifts from the sidewall to the bottom of the feature.

The thin layer of conductive condensation is effective in spreading charges throughout the feature, which then reduces the potential. In response to the disparity in charge delivered to the top of the feature (dominantly negative) compared to the bottom of the feature (dominantly positive), there is a transient in potential that redistributes charge and polarizes the conductive water layer. As the intrinsic charge density increases, the reduction in potential increases indicating that polarization of intrinsic charges is the dominant effect. In these simulations, high conductivity water layers produce less bowing of the feature but more taper than low conductivity conditions, while having a nominal reduction in etch rates.

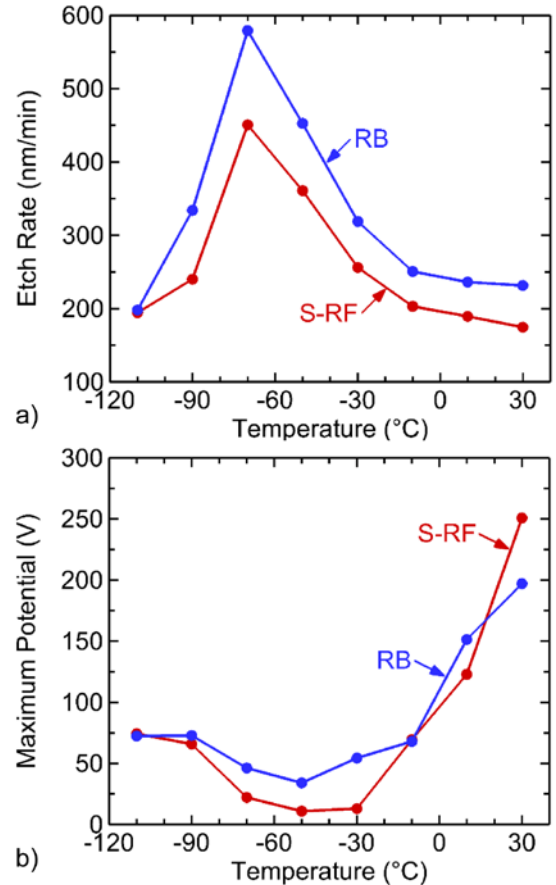
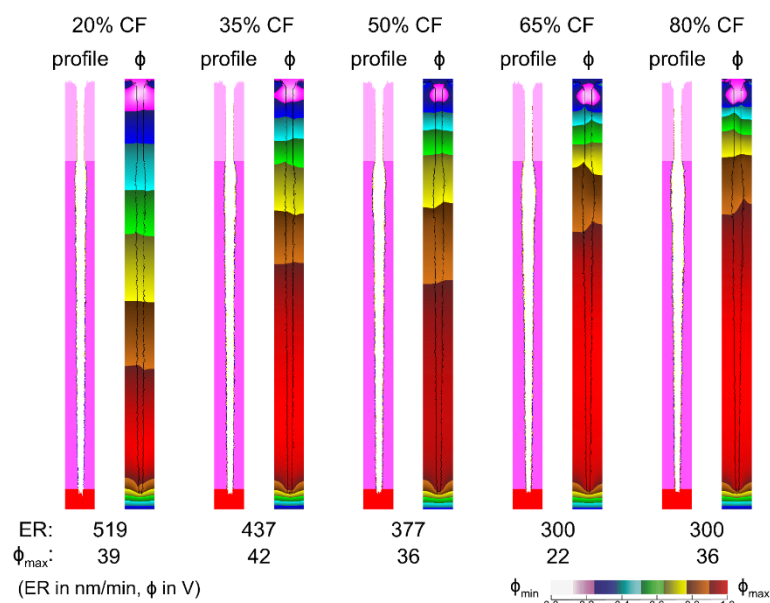


Figure 5 – Etch properties as a function of substrate temperature contrasting RB (CF = 50) and sinusoidal (S-RF) bias waveforms. a) Etch rate and b) maximum in feature potential.

In CPE, adsorption probabilities of etch precursors generally increase with decreasing substrate temperature. In the case of HF based CPE of SiO₂, this adsorption leads to a few nm thick acid layers. A consequence of increasing adsorption probabilities is a higher etch rate, which is a desirable outcome. However, for sufficiently low substrate temperature, water condensation occurs which produces undesirably thick acid layers. Ions are less able to penetrate the thick condensation layers to activate etching at the SiO₂ interface, and so etch rate decreases or etching terminates. Etch profiles and electrical potential are shown in Fig. 4 for different substrate temperatures, $T_{sub} = +10$ °C to -110 °C. The bias uses a RB waveform at 2000 W with CF = 50%. The etch rate (580 nm/min) is maximum, and electrical potential (46 V) is minimum for $T_{sub} = -70$ °C. For higher T_{sub} , adsorption rates decrease, reducing etch precursors and etch yield, resulting in a lower etch rate. With thinner conductive adsorption layers, the in-feature electric potential increases. For lower T_{sub} , adsorption rates increase leading to condensation, which terminates etching. With less surface area covered by conductive water layers to dissipate charge, the in-feature electric potential increases.

Figure 6 – Feature profile and electric potential for CPE of SiO₂ with RB having a constant 4000 V for different CF. ER = etch rate and ϕ = potential. The bias is pulsed with a duty cycle adjusted to deliver a constant average power. $T_{sub} = -70$ C.



Over a range of $T_{sub} = +30$ °C to -110 °C, biases using the RB waveform (CF = 50) generally produce higher etch rates, as shown in Fig. 5, compared to sinusoidal bias waveforms. These higher etch rates result from the IEADs for RB being more monoenergetic at higher energies, which increases the average etch yield. RB waveforms produce narrower angular distributions, which result in more specular scattering from sidewalls. This more favorable scattering delivers more energy to the etch front. However the in-feature electrical potential is a weak function of the bias waveform. The electrical potential is dominated by the conductivity of the surface layers, which is mostly determined by T_{sub} . When the electric potential is smaller with RB waveforms, this is likely due to less sidewall scattering.

For CPE conditions, the value of the in-feature potential is dominated by the conductivity of the water (acid) layers. As such, the in-feature potential is also a weak function of the cathodic fraction of the RB waveform. For example, profiles and electric potential are shown in Fig. 6 with CF = 20 to 80%. The bias voltage amplitude is 4000 V. The bias was pulsed with the duty cycle (DC, fraction of the pulsed period with bias on) being adjusted to deliver a constant average power of 2000 W. The etch rate increases with decreasing CF as the DC must increase to maintain a constant power. There is also less bowing of the feature at lower CF due to thicker adsorption layers which controls lateral etching. However, the electrical potential is a weak function of CF. The variation in electric potential across these values of CF are largely statistical due to the randomly varying water coverage and thickness.

IV. CONCLUDING REMARKS

Charging of HAR features during cryogenic plasma etching of SiO₂ in dual frequency CCPs was discussed based on results from reactor and feature scale models. During CPE, in-feature electric potentials are generally

less positive than for conventional etching due to the adsorption of water layers on feature sidewalls, and their acidification by hydrolysis of HF which increases conductivity. Although RB waveforms produced higher etch rates, the electrical potential is a weak function of the bias waveforms for cryogenic conditions. During CPE, the potential is dominated by the conductivity of the water layers, which is to first order a function of substrate temperature.

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