Profile Control in High Aspect Ratio Plasma Etching: Low Frequency and Passivation

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Abstract: The trend towards 3-dimensional structures in microelectronics fabrication presents challenges for plasma etching of high aspect ratio (HAR) features. One strategy to address this challenge is to operate substrate biases with lower frequencies. This strategy has been computationally investigated for bias frequencies of 250 kHz to 5 MHz in inductively coupled plasma etching of p-Si in $Ar/Cl_2/O_2$ for deep trench isolation having an aspect ratio of 50. We found that critical dimensions generally improved at lower bias frequencies due the ion fluxes to the wafer having narrower angular distributions, higher energy and better angular uniformity.

Keywords: plasma-liquid interactions, plasma modelling, plasma medicine, atmospheric pressure plasma

1. Introduction

As the rate of decrease in feature size in microelectronics devices begins to slow, greater functionality is being achieved by fabricating 3-dimensional devices. One consequence of fabricating 3D devices is the need to plasma etch high aspect ratio (HAR) features [1]. (AR or aspect ratio is the height of the feature divided by width). For example, 3D-NAND memory structures require etching of vias through hundreds of alternating layers of silicon dioxide and silicon-nitride (ONO) having AR > 100 [2]. These dielectric plasma etches are typically performed in fluorocarbon gas mixtures using capacitively coupled plasmas (CCPs). Another example of HAR plasma etching is deep trench isolation (DTI) which is used to isolate 3D logic structures from interfering with each other [3]. These DTI etches, usually in Si, are performed in halogen based mixtures (e.g., HBr/Cl_2) in inductively coupled plasmas (ICPs) with a substrate bias.

Achieving anisotropic plasma etching of these HAR feature requires a narrow-angular distribution of incident ions and some form of side-wall passivation to prevent bowing of the sidewalls. With the goal of narrowing the angular distribution of ions, high voltage (several keV) and very-low-frequency (VLF) substrate biases are often used (100s kHz), placing ion transit through the sheath in the thin-sheath limit. (The thin sheath limit refers to ions being able to transit the sheath in a fraction of the RF period. In fact, the use of large voltages produces physically thick sheaths.) In fluorocarbon gas mixtures, sidewall passivation often naturally occurs by polymer deposition. However in conductor (Si) etch in halogen gas mixtures, there is no natural passivation that prevents lateral etching and bowing. As a result, O_2 is often added to the mixture to oxidize the surface, and so slow the rate of spontaneous etching. In both cases (dielectric and conductive) of HAR etching, etch products must diffuse from the bottom of the feature out of the feature, a process that may involve hundreds of collisions with the sidewall. With this large number of collisions, even small sticking coefficients will result in redeposition of etch products. The redeposition is, in some ways, a beneficial by-product as it provides passivation against lateral etching. However, too much redeposition can lead to tapering of the feature and ultimately an etch stop.

In this paper, we report on results from a computational investigation of profile control of HAR features using VLF biases in the presence of passivation. The focus of our studies is plasma etching of DTI features etched in Si using an $Ar/Cl_2/O_2$ ICP with a VLF substrate bias.

2. Description of the Models

This investigation was performed using two modelling platforms. The reactor scale was addressed using the HPEM (Hybrid Plasma Equipment Model) [4]. The HPEM is a 2-dimensional first principles, multi-fluid simulator for plasma transport, chemistry and plasma-surface interactions. An outcome of the HPEM is energy and angularly resolved fluxes of reactive species to surfaces in contact with the plasma. The MCFPM (Monte Carlo Feature Profile Model) is a voxel based simulator which uses as input the angle and energy resolved fluxes from the HPEM [4]. The MCFPM represents the feature using a cubic mesh (voxels) which represent different materials. The voxels are added (deposition), removed (etching) or have their material identity changed (passivation) based on a gas-to-surface reaction mechanism. Reactions may also occur between surface species and through implantation.

3. Feature Control for VLF Biases

The base case is an ICP sustained in an $Ar/Cl_2/O_2$ = 0.90/0.09/0.01 mixture at 15 mTorr with 500 W of source power at 10 MHz, as shown in Fig. 1. The reactor is cylindrically symmetric with a flat, spiral coil. The powered substrate holding the wafer is surrounded by a quartz focus ring. The dielectric window also serves as a showerhead, with pumping being annular around the substrate. In order to facilitate a side-to-side comparison of different bias frequencies, the bias amplitude was held constant at 1000 V, acknowledging that this may produce different bias powers. (It is more typical to set power as opposed to voltage.) Bias frequencies, f_{bias}, were varied from 250 kHz to 5 MHz.

Electron density is shown in Fig. 1 for bias frequencies of 250 kHz and 5 MHz. The time of the image is for the peak of the cathodic cycle – when the bias is most negative. At f_{bias} = 250 kHz, there is, for all practical purposes, no electron heating by the sheath other than by secondary electron emission. The majority of the ionization comes from the ICP source power, producing a maximum electron density of 6.5 × 10^{10} cm^{-3}. At f_{bias} = 5 MHz, the frequency is high enough that there is sheath heating of electrons, producing additional ionization. This increases the maximum electron density to 9.5 × 10^{10} cm^{-3}. In spite of the higher electron density, the sheath is thicker at 5 MHz with there being a small slope to the sheath edge. At f_{bias} = 250 kHz, the sheath is essentially flat.

The differences in sheath thickness and slope in the sheath are partly a consequence of the different contributions of displacement vs conduction current through the sheath at the two frequencies. The dielectric (quartz) focus ring surrounding the powered substrate fully charges during the RF cycle at f_{bias} = 250 kHz while not fully charging at 5 MHz. (The RF period differs by a factor of 20.) The full charging of these materials at 250 kHz reduces the extension of the sheath across the dielectric focus ring, thereby reducing the slope of the sheath across the wafer. At f_{bias} =5 MHz, the dielectric does not fully charge, resulting in displacement current flow through the dielectric throughout the cycle, which extends the sheath further across the dielectric. The extension produces some sheath curvature.

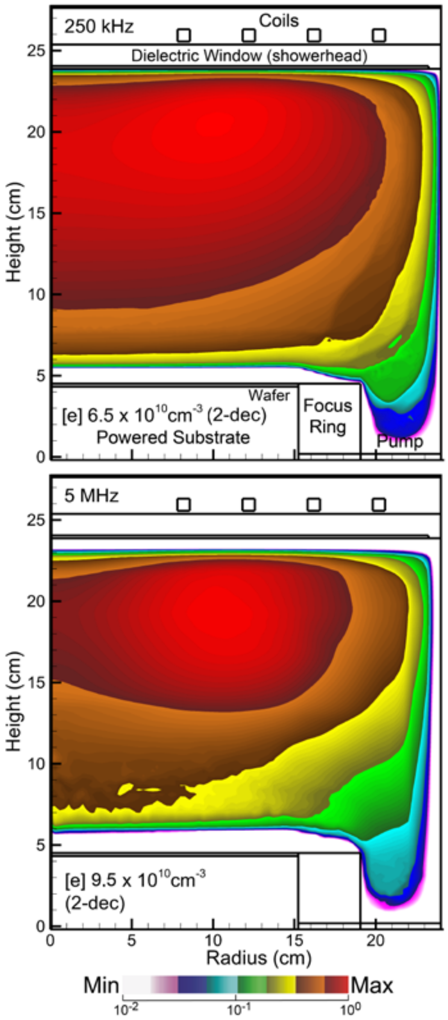

Fig. 1. Electron density at the peak cathodic (most negative) part of the RF cycle for (top) 250 kHz and (bottom) 5 MHz.

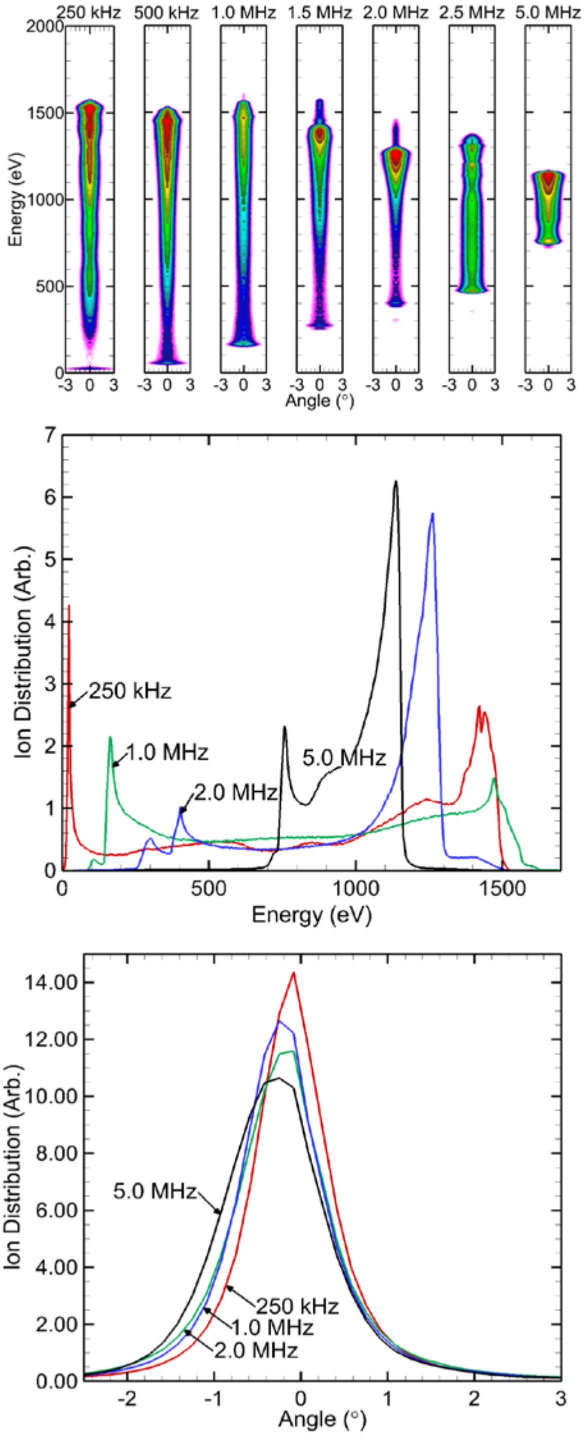

Fig. 2. (top) IEADs (sum of all ions) incident onto the substrate for bias frequencies of 250 kHz to 5 MHz. (middle) Angle integrated energy distribution. (bottom) Energy integrated, angular distribution.

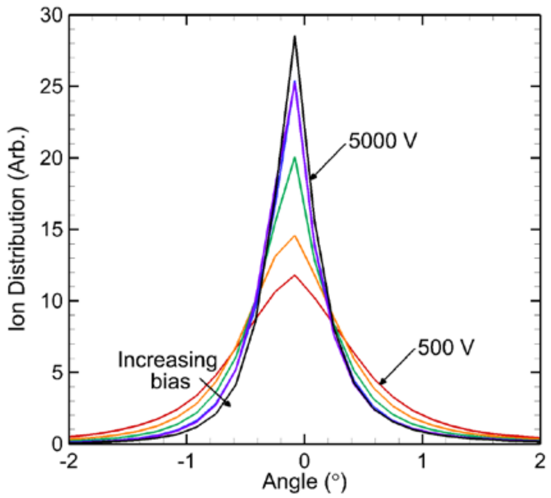

Fig. 3. Energy integrated, angular distribution for all ions for 250 kHz bias for voltage amplitudes of 500 V to 5000 V.

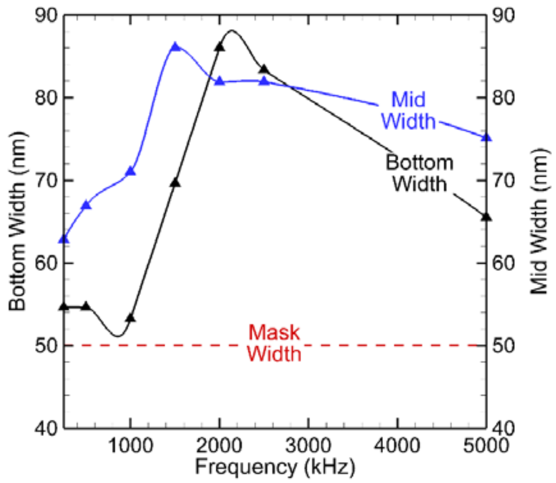

Fig. 4. Critical dimension of Si trench after fully etching to an AR=50 as a function of bias frequency.

The change in sheath thickness, slope and plasma density with bias frequency produces systematic trends in the ion energy and angular distributions (IEADs) onto the wafer. (See Fig. 2.) In transitioning from f_{bias} = 250 kHz to 5 MHz, ion transport changes from the thin-sheath limit (low frequency) to the thick sheath limit (high frequency). That is, ion transit through the sheath requires a fraction of the RF period at the lower frequency while requiring many RF periods at the higher frequency. In doing so, the energy range of the ions decreases from 1500 eV at low bias frequency to 500 eV at high bias frequency. At f_{bias} = 250 kHz, the angular distribution is nearly symmetric across the surface normal. As the bias frequency increases and the sheath begins to tilt, the angular distribution becomes more asymmetric.

The asymmetry of the ion angular distribution is, for these conditions, more a function of frequency than power or voltage. For example, the energy integrated ion angular distribution is shown in Fig. 3 for f_{bias} = 250 kHz and voltage amplitudes of 500 V to 5000 V. The symmetry of the angular distribution is retained across this range of voltage over which the thickness of the sheath varies by a factor of 2. The desired effect of increasing voltage is to narrow the angular distribution, and this goal is achieved.

Profile control is often measured by the critical dimensions (CDs) of features. For example, a trench with no undercutting of the mask or bowing, would have a width, or CD, equal to the mask opening at all heights in the feature. An example of profile control using frequency is shown in Fig. 4. The feature is a trench etched into poly-Si having an erodible mask thickness of 500 nm and opening of 50 nm. The full height of the Si is 2500 nm, producing and AR of 50. The Si sets on SiO_2 which acts as a partial stop layer. After fully etching the feature, the width of the feature was measured at mid-height and at the bottom of the feature. The results are shown in Fig 4 as a function of bias frequency.

Low frequencies generally produce widths at mid-height and at the bottom of the feature that are close to the mask width. These measurements indicate less bowing and less sidewall slope. This more ideal feature results from the narrower angular distribution and higher symmetry of the IEAD that the lower frequency produces. That said, these results are also very sensitive to passivation by etch products and by oxidation of the side wall that prevents lateral spontaneous etch. Smaller admixtures of O_2 produce insufficient sidewall oxidation to prevent lateral etching, resulting in bowing of the feature. Larger O_2 fractions produce thicker SiO_2 sidewall films, resulting in tapering.

4. Concluding Remarks

Profile control of HAR features akin to deep trench isolation (DTI) in poly-Si was computationally investigated in an ICP sustained in $Ar/Cl_2/O_2$ mixtures using bias frequency as a variable. For the conditions of this study, lower frequencies generally produced more uniform sheath thickness, higher ion energies and narrower angular distributions, all of which contribute to features having more uniform critical dimensions.

5. References

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