Etching of silicon dioxide using a "remote" capacitively coupled plasma source

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Abstract: Fabrication of lithographic masks for microelectronics processing is often a multi-step operation which entails plasma etching of thin dielectric layers while requiring high selectivity process. This step is often performed using a dual-frequency capacitively coupled (DF-CCP) having a large gap to serve the function of being a remote plasma source. A computational investigation was performed of etching of thin dielectric layers as found in multi-layer optical masks. The DF-CCP was sustained in an $Ar/C_4F_8/O_2$ mixture at 15 mTorr with a 60 MHz source power on the top electrode and a 10 MHz bias power on the lower electrode.

Keywords: plasma etching, capacitively coupled plasmas, silicon dioxide

1. Introduction

The reduction in feature size in microelectronics processing has resulted in increasing demands for lithography to define those features. Processes such as self-aligned double patterns have been implemented to increase device density while reducing production cost [1]. However, these processes also present challenges in fabricating the masks. The lithographic stack typically consists of several layers of different materials (e.g., anti-reflecting coatings) that are plasma etched with several steps. Since the dimensions of these layers can be only a few to tens of nm, the etch must be highly selective. When etching dielectric materials, the process recipe typically contains fluorocarbon gases. At the same time, it is desirable to have fine control over radial and ion fluxes to the substrate. This control is often obtained by using dual frequency capacitively coupled plasmas (DF-CCP) having a large electrode gap. A high frequency applied to the top electrode controls the magnitude of ion fluxes. A low frequency applied to the lower electrode controls ion energy distributions (IEDs) to the substrate. The large gap makes the plasma generation appear to be remote, and so affords additional control over the composition of radical and ion fluxes.

Precision etch of dielectric materials which have high selectivity was computationally investigated using 2-dimensional reactor scale models and 3-dimensional feature scale models. Parametric investigations of various plasma source designs and gas mixtures were performed to satisfy dielectric trench/via etch requirement [2]. In this abstract, simulations of a large gap DF-CCP for SiO_2 line and space trench etch will be discussed.

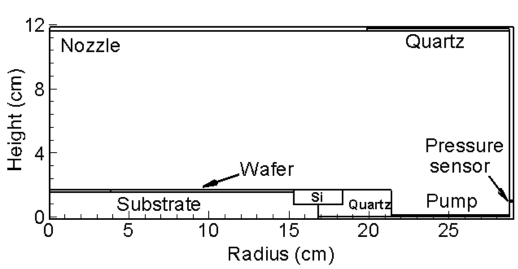

Fig. 1. Schematic of the DF-CCP chamber, HF power at 60 MHz is applied to the top electrode and LF power at 10 MHz is applied to the bottom electrode.

2. Description of the model

Modeling of the etching reactor scale plasma properties

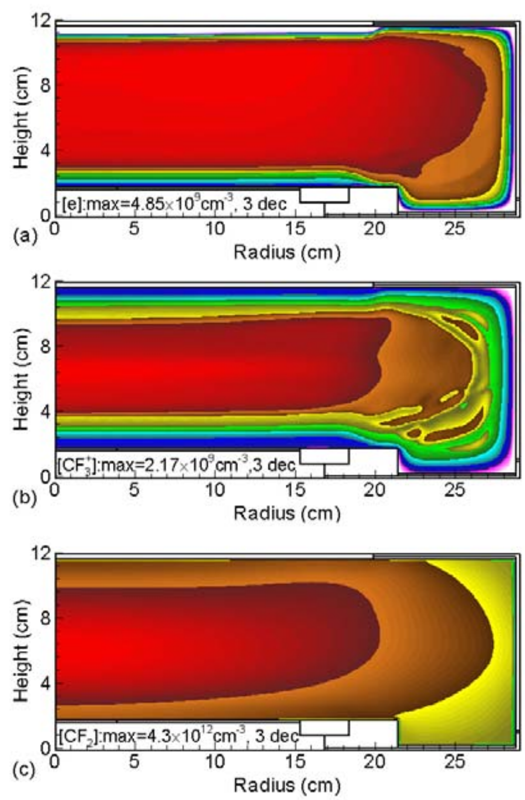

Fig. 2. Plasma properties in the DF-CCP (a) Electron density; (b) CF_3^+ ion density; and (c) CF_2 neutral density from HPEM simulation sustained in 15 mTorr, $Ar/C_4F_8/O_2$ = 400/7/3 sccm, 60 MHz/10 MHz = 250 W/100 W.

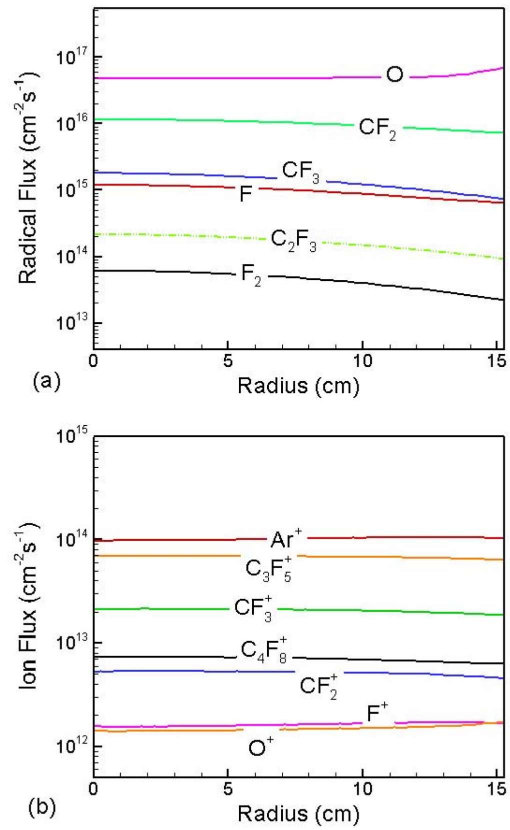

Fig. 3. Reactant fluxes to the surface of the wafer. (a) Neutral fluxes and (b) ion fluxes.

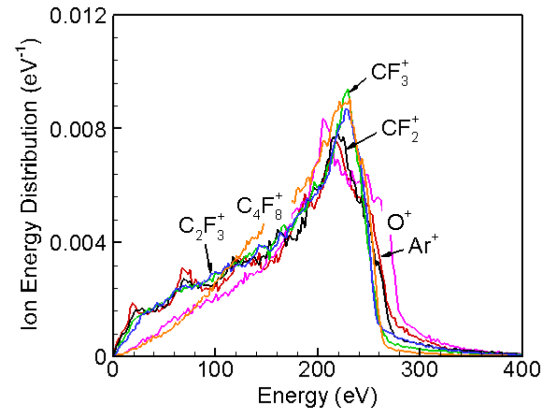

Fig. 4. Ion Energy Distribution Functions (IEDFs) on the surface of wafer from PCMCM.

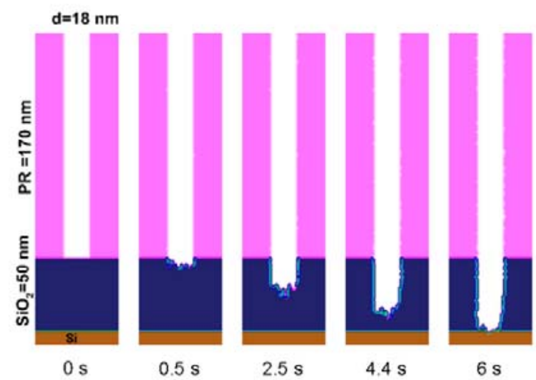

Fig. 5. The time evolution of the etch profile from MCFPM. The height of SiO_2 is 50 nm with a 170 nm photoresist mask and an underlying Si layer.

was performed using the Hybrid Plasma Equipment Model (HPEM) [3]. The ion energy and angle distributions (IEDs and IADs) to the wafer were calculated by the Plasma Chemistry Monte Carlo Module (PCMCM). The feature scale profile was simulated by the Monte Carlo Feature Profile Model (MCFPM) [4]. A CCP source with gap distance of electrodes at 10 cm (shown in Fig. 1) was used. The top electrode was driven by a 60 MHz high frequency (HF) at 250 W, and a 10 MHz low frequency (LF) at 100 W power was applied to the bottom electrode. An $Ar/C_4F_8/O_2$ gas mixture was uniformly injected into the chamber from the top electrode with a rate of 400/7/3 sccm. The gas temperature and pressure in the chamber were initially 350 K and 15 mTorr, respectively.

3. Plasma properties and etch feature

The time averaged electron, CF_3^+ ion, and CF_2 neutral densities are shown in Fig. 2. The electron density peaks at 4.45×10^9 cm^{-3} near the top electrode side owing to HF power deposition, while decreasing 3 magnitudes near the wall and pump out boundaries. The densities of CF_3^+ ion and CF_2 neutral peak at 2.17×10^9 cm^{-3} and 4.3×10^{12} cm^{-3}, respectively. Edge effects at the outer radius of the wafer and over the focus ring often produce radial non-uniformities in narrow-gap CCPs. In this large gap CCP, there non-uniformities are mediated, and the reactant densities are fairly uniform across the wafer. The resulting fluxes to the wafer are also uniform, as shown in Fig. 3. Fluxes of radicals are 10-100 times higher than ions, in part due to the large gap which provides opportunity for neutralization reactions to occur. CF_2 and CF_3 are the major radicals followed by C_2F_3. The flux of CF_2, 1.1×10^{16} cm^{-3}s^{-1}, is an order of magnitude higher than F, 1.2×10^{15} cm^{-3}s^{-1}, while is lower than the flux of O atoms. Large fluxes of O will chemically etch the CF_x polymers that deposit on the wafer. The flux of Ar^+ to the wafer is 1.0×10^{14} cm^{-3}s^{-1}, which is two magnitudes lower than CF_2, while still playing an important role in chemical sputtering.

The cycle averaged IEDs are shown in Fig. 4. The ranges of ion energies are up to nearly 400 eV with peaks at about 210 eV mainly due to the LF power deposition. The HF has a small influence on IEDs owing to the remote gap distance, while producing minor peaks bellow 100 eV.

By using the energies, angles, and fluxes of ions and neutrals, a small aspect ratio (AR) SiO_2 dielectric trench with height at 50 nm and width at 18 nm was etched as shown in Fig. 4. This is the type of features found in photolithographic stacks and which require high selectivity. From the time evolution of the etch profile shows that small amounts of polymers are deposited on the sidewall of the trench. For this pattern, the ratio of PR height (170 nm) to trench width only allows ions with angles smaller than 6° to reach the surface of the wafer. Obviously, the anisotropy properties of ions matched well with the profile leaving a collimated sidewall trench with time evolution. The mean etch rate is as high as 83 Å/s while having high selectivity to the underlying Si.

4. Concluding remarks

Etching of a low AR SiO_2 trench over Si was investigated using a large gap dual-frequency CCP reactor sustained in $Ar/C_4F_8/O_2$ mixture. HF power was applied to the top electrode to generate a high density plasma. The large gap distance allows these plasmas to uniformly diffuse over the electrodes. The O, CF_2, CF_3 and F neutrals are the major radicals with their fluxes ranging from 10^{15} $cm^{-3}s^{-1}$ to 10^{17} $cm^{-3}s^{-1}$. These species in large part regulate the thickness of polymer layers on the wafer. The flux of Ar^+ is 1-2 magnitudes lower than CF_x neutrals, producing fairly polymerizing fluxes which produce selective etches.

5. Acknowledgement

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6. References

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