Fluorocarbon assisted atomic layer etching of SiO_2 using low temperature cyclic Ar/CHF_3 plasma

Stefano Dallorto[a,b,c], Andy Goodyear[c], Mike Cooke[c], Scott Dhuey[a], Julia E. Szornel[a], Ivo W. Rangelow[b], Stefano Cabrini[a]
[a] Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, 94720, United States
[b] Ilmenau University of Technology, Dept. of Micro- and Nanoel. Syst., 98684, Germany
[c] Oxford Instruments, 300 Baker Avenue, Suite 150, Concord, MA 01742, United States

Single digit nanometer semiconductor manufacturing is increasingly demanding atomic scale process controllability to further decrease critical dimensions and pitches.[1] High etching precision and material selectivity become essential in the atomic scale era. Plasma based atomic layer etching (ALE) shows promise to attain atomic etch precision, enhancing energy control and reaction chemistry control.[2, 3]

The most basis ALE process is separated into a passivation step and an etching step. Passivation is accomplished creating a thin reactive surface layer with well-defined, angstrom-scale thickness. Etching is then accomplished removing only the passivated surface. The use of two self-limited reactions for each of these steps enables the fluxes of neutral and charged particles to be independently optimized despite their different transport methods.[4] Here we study a Fluorocarbon(FC)-based ALE process for controlling the etching of silicon dioxide at the atomic level. Figure 1 shows the schematic of atomic layer etching process using Ar plasma and CHF_3 gas. In this technique, an Ar plasma is maintained continuously through the process, below the energy threshold for SiO_2 sputtering. A fluorocarbon chemistry is then introduced via CHF_3 pulsing (Figure 1 (a)) to provide the reactant absorption. Subsequently, once the gas pulse has concluded, bias power is introduced to the Ar plasma, to provide enough energy to initiate reaction of the FC with the SiO_2 (Figure 1(b)). In ideal ALE, each of the steps is fully self-limiting for over exposure to increase uniformity on the microscale (wafer) and atomic scale.

With the goal of achieving self-limiting FC-based ALE, we investigated the etch step using low energy Ar ion bombardment. By carefully tailoring the energy of ion bombardment, it is possible to control the etching depth to approach a self-limiting behavior. The impact of various process parameters on the etch performance is established. We demonstrated that the SiO_2 amount etched per cycle (EPC) is strongly affected by the forward bias plasma power, as well as the substrate temperature (Figure 2(a)). The substrate temperature has been shown to play an especially significant role, at -10 °C the contributions to chemical etching coming from fluorine and fluorocarbon compounds from chamber walls are minimized and a quasi-self-limiting behavior ALE is observed.
Figure 2(b)-(f) showed the Cr features after being etched for 60 ALE cycles with the optimal ALE self-limiting conditions. Feature trenches vary from 20-200 nm and were defined using metal lift-off. Overall, using the cyclic CHF_3/Ar ALE at -10 °C, we reduced geometric loading effects during etching and reached aspect ratio independent etching, with great potential for significant improvement in future etching performances.

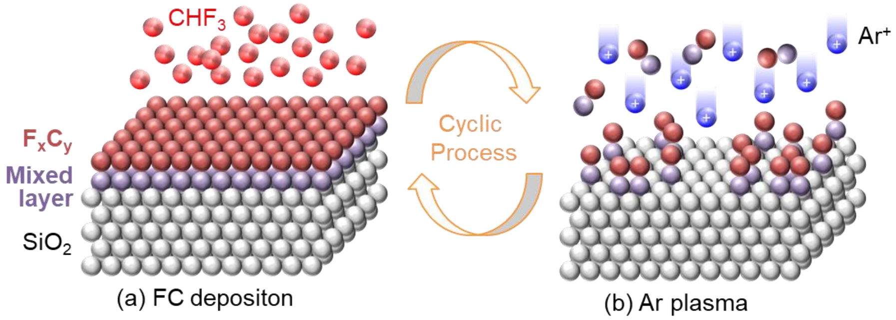

Figure 1. Schematic of the cyclic ALE approach employed consisting of repeating deposition step and etch step. (a) Fluorocarbon deposition: FC film has an effective reaction depth to form the mixed layer on SiO_2 film. (b) Ar plasma etch: Ar plasma removes the mixed layer and also residual FC film, leaving no fluorine on SiO_2 film.

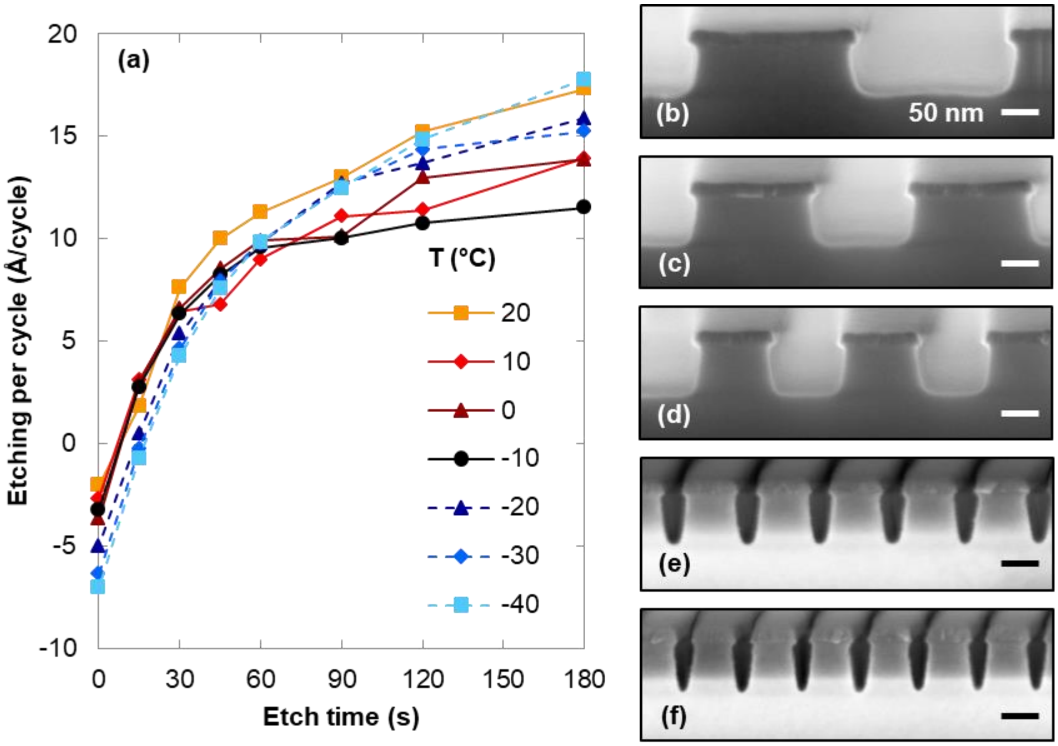

Figure 2. (a) SiO_2 ALE under increased Ar plasma etch time at different temperatures and at low electrode voltage (-9 V). At -10°C ALE is self-limiting. (b)-(f) SiO_2 etching of features between 20 nm and 200 nm with 60 cycles CHF_3-based ALE using 15 nm lift-off chromium mask.

[1] Present, I., *Cramming more components onto integrated circuits.* Readings in computer architecture, 2000. **56**.

[2] Kanarik, K.J., et al., *Overview of atomic layer etching in the semiconductor industry.* Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films, 2015. **33**(2): p. 020802.

[3] Oehrlein, G., D. Metzler, and C. Li, *Atomic layer etching at the tipping point: an overview.* ECS Journal of Solid State Science and Technology, 2015. **4**(6): p. N5041-N5053.

[4] Agarwal, A. and M.J. Kushner, *Plasma atomic layer etching using conventional plasma equipment.* Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films, 2009. **27**(1): p. 37-50.