PROFILE ANGLE CONTROL IN SiO_2 DEEP ANISOTROPIC DRY ETCHING FOR MEMS FABRICATION

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ABSTRACT

We report a recent breakthrough to control profile angle for SiO_2 Deep Anisotropic Dry Etching (SDADE). Our study reveals that gas residence time is the key parameter to control profile angle. Moreover, we show that it is possible to control profile angle, SiO_2 etch rate and SiO_2 selectivity to Si mask independently. Finally, the optimized process has the following performances: angle profile: 89.8°, SiO_2 etch rate: 500 nm / min, selectivity: 18: 1.

1. INTRODUCTION

SiO_2 Deep Anisotropic Dry Etching (SDADE) is increasingly needed for optical and fluidic MEMS. However, most recently published studies on SiO_2 etching only deal with etching and selectivity mechanisms in fluorocarbon inductively coupled plasmas (ICP) [1-5], but not with profile angle control. Moreover the etching depth is always inferior to 3 µm [3, 5-7], those studies mostly dealing with microelectronic applications where high aspect ratio but small etching depth are targeted. Thus, it seems our work is the first study to be published on the factors acting on profile angle for important thicknesses (≥ 9 µm). And yet, in SDADE, profile angle control is as important as SiO_2 etch rate and selectivity to mask.

2. EXPERIMENT

Preliminary results with C_4F_8 / CH_4 plasmas convinced us that gas residence time could be a major factor acting on profile angle: the lower gas residence time was, the righter profile angle was. Since we were targeting a profile angle at 90°, we tried to minimize gas residence time. In order to reach gas residence time as low as possible, a dilution of the C_4F_8 / CH_4 mixture with an inert gas has been decided. Indeed, gas residence time t and total gas flow rate Q are related as follows:

$$t = \frac{P \times V}{Q}$$

where P is the working pressure and V the volume of the reactor. Thus, increasing Q makes it possible to decrease gas residence time.

He and Ar have then been studied as possible candidates to dilute the initial C_4F_8 / CH_4 mixture. The effect of He and Ar flow rate on profile angle at constant gas residence time is reported on Figure 1. Gas residence time was maintained at 100 ms by adjusting process pressure.

He turned to be best candidate since profile angle is not negatively affected. Profile angle is even righter at high He flow rate. SiO_2 etch rate is also improved with He (Figure 2). On the contrary, dilution with Ar alters both profile angle (Figure 1) and SiO_2 etch rate (Figure 2).

Our first results on profile angle obtained in a C_4F_8 / CH_4 / He plasma for different residence times are presented on Figure 3.

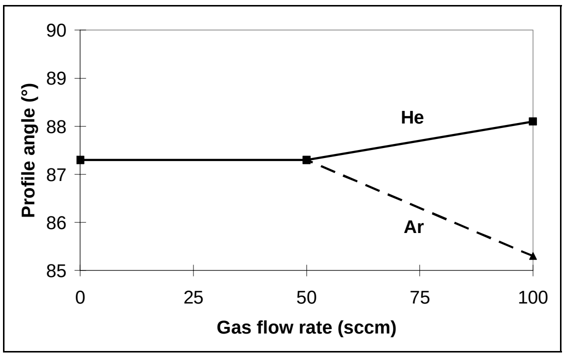

Figure 1: Profile angle as a function of He and Ar flow rate

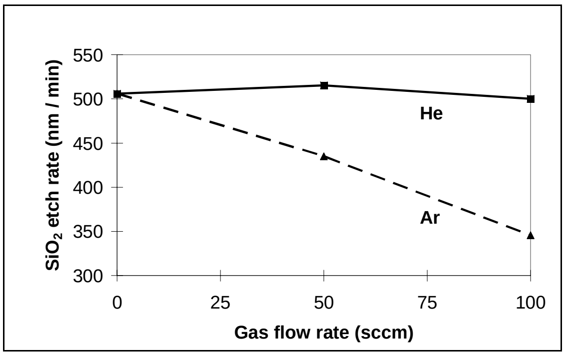

Figure 2: SiO_2 etch rate as a function of He and Ar flow rate

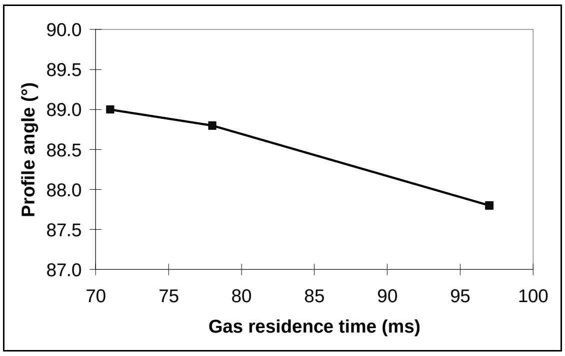

Figure 3: Profile angle as a function of gas residence time

In order to study in detail SDADE, a fractional factorial design of experiments has been carried out using Umetrics's MODDE 6.0 software. The analysed factors were C_4F_8 and CH_4 flow rate, substrate bias voltage, ICP radiofrequency (RF) power and gas residence time. He flow rate was voluntarily fixed at the flow rate allowing us to reach the lowest gas residence time and gas residence time was then adjusted with the working pressure.

All experiments have been performed with the high-density ICP reactor Alcatel AMS 200 DE. The etched substrates were 100 mm diameter, 525 µm thick Si wafers with 9 µm thick SiO_2 (Low Temperature Oxide) and a mask of 2 µm thick polycrystalline Si (Low Pressure Chemical Vapour Deposition).

3. RESULTS AND DISCUSSION

Figures 4(a), 4(b) and 4(c) show the effects of factors and main interactions on profile angle, SiO_2 and Si etch rate respectively: the column heights represent the importance of the effect and the bars represent the uncertainty.

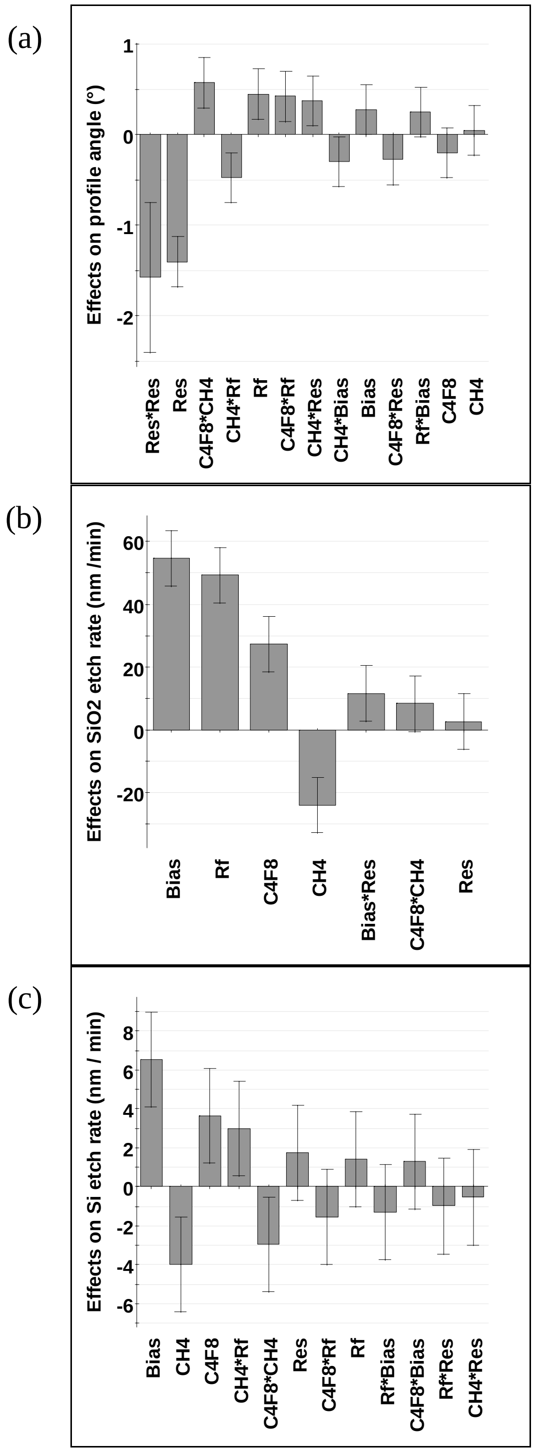

Figure 4: Effects on profile angle (a), SiO_2 etch rate (b) and Si etch rate (c)
(C_4F_8 = C_4F_8 flow rate, CH_4 = CH_4 flow rate, Bias = substrate bias voltage, Res = gas residence time, Rf = ICP RF power)

Profile angle turned out to be mainly controlled by residence time (Figure 4a), thus confirming our first tests: increasing gas residence time reduces drastically profile angle. Moreover, compared to other experimental parameters, gas residence time has a very little impact on SiO_2 and Si etch rate which enables to control profile angle regardless of SiO_2 etch rate and selectivity. Figure 5 presents profile angle as a function of gas residence time while other experimental parameters were kept at their average value.

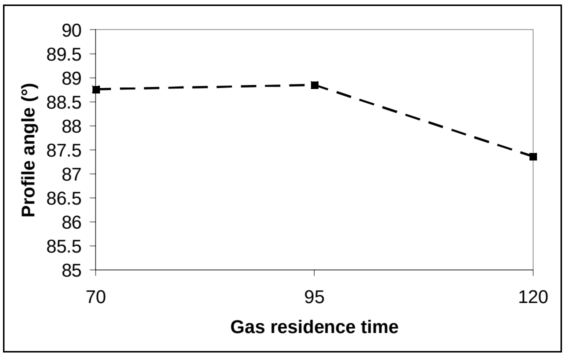

Figure 5: Profile angle as a function of gas residence time

Concerning SiO_2 and Si etch rate, substrate bias voltage, ICP RF power and C_4F_8 have a positive effect. On the other hand, CH_4 has a negative effect (Figure 4b and 4c). Moreover a strong interaction exists between C_4F_8 and CH_4 as shown on Figures 6 and 7. This interaction makes it possible to set selectivity. Indeed, increasing the CH_4 / C_4F_8 ratio reduces both SiO_2 and Si etch rate. However, Si etch rate is reduced in a more important way resulting in an increase of selectivity. Those results are in perfect agreement with common knowledge on selectivity mechanisms in fluorocarbon plasma: the addition of H and C atoms increases the C / F ratio which is known to increase the polymer deposition responsible of selectivity between SiO_2 and Si.

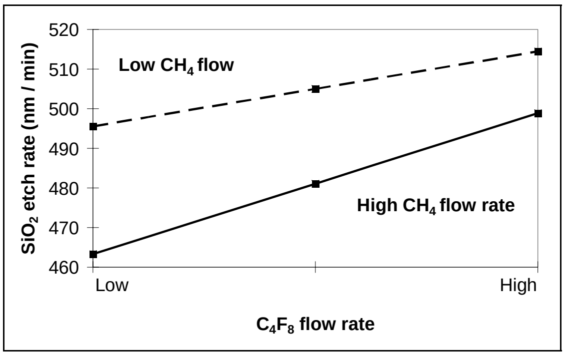

Figure 6: C_4F_8 / CH_4 interaction effects on SiO_2 etch rate

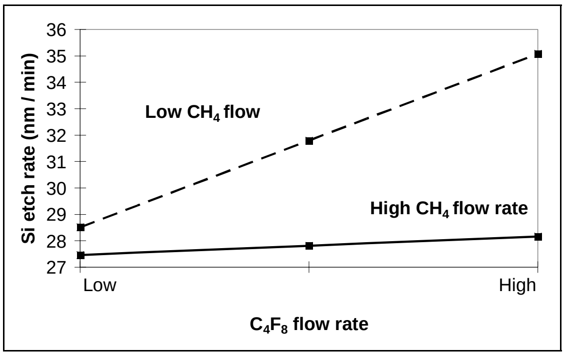

Figure 7: C_4F_8 / CH_4 interaction effects on Si etch rate

Finally, we present SEM pictures of 9 µm thick LTO etching performed with the original process on Figures 8 and 9 (Angle profile: 85°, SiO_2 etch rate: 390 nm / min, Selectivity: 14.4:1) and with the optimized process on Figures 10 and 11 (Angle profile: 89.8°, SiO_2 etch rate: 500 nm / min, Selectivity: 18:1). Figure 12 depicts a successful attempt on a bulk fused silica wafer with the optimized process.

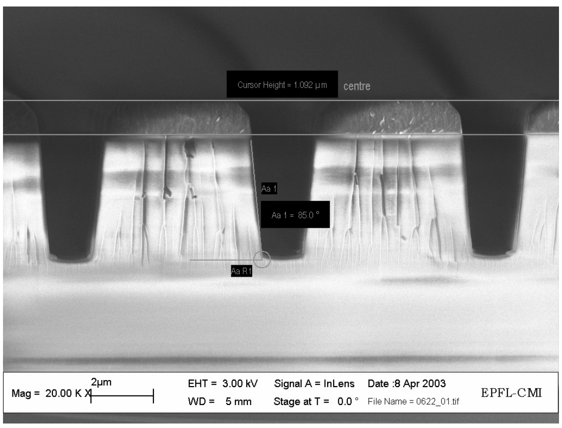

Figure 8: SEM picture of 2 µm wide SiO_2 trenches etched with the original process

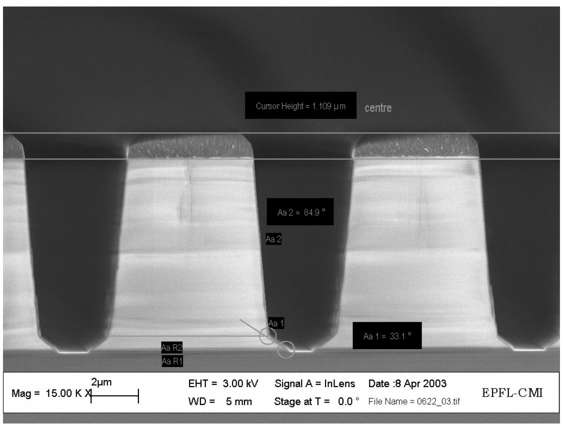

Figure 9: SEM picture of 5 µm wide SiO_2 trenches etched with the original process

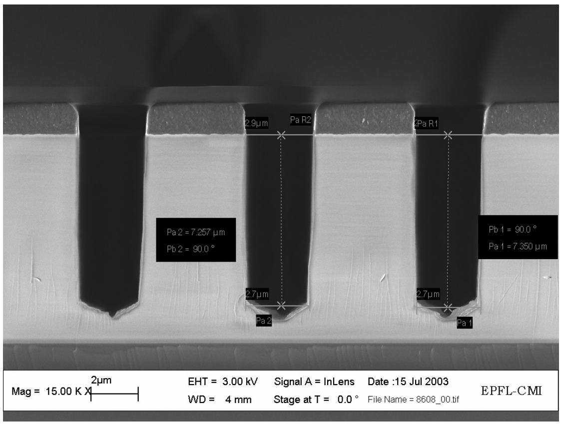

Figure 10: *SEM picture of 2 µm wide SiO_2 trenches etched with the optimized process*

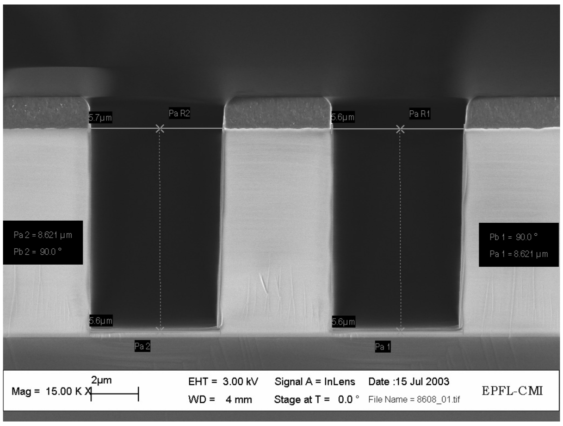

Figure 11: *SEM picture of 5 µm wide SiO_2 trenches etched with the optimized process*

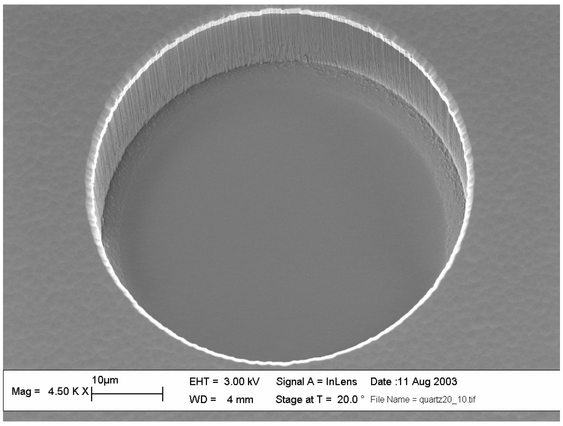

Figure 12: SEM picture of a hole etched in a fused silica wafer (depth: 20 µm, diameter: 50 µm)

CONCLUSION

Gas residence time is the key parameter to control profile angle. To achieve SDADE, attention must then be focused on reducing gas residence time as much as possible. In order to reach low gas residence time, a dilution of the fluorocarboned chemistry with He is efficient providing process pressure is kept under 1 Pa typically, in order to avoid collisions between species due to a too short mean free path.

Moreover, it is possible to control profile angle (with residence time), SiO_2 etch rate (with substrate bias voltage, ICP RF power and C_4F_8 flow rate) and SiO_2 selectivity to mask (with CH_4 / C_4F_8 ratio) independently. Finally, the optimized process has the following performances: angle profile: 89.8°, SiO_2 etch rate: 500 nm / min, selectivity: 18: 1.

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