Very High Aspect Ratio Deep Reactive Ion Etching of Sub-micrometer Trenches in Silicon

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Abstract— **This paper focuses on Deep Reactive Ion Etching (DRIE) of sub-micrometer features. Very high aspect ratios up to 160:1 on trenches of 250 nm have been achieved using the Bosch process and 120:1 on 35 nm-wide trenches using a cryogenic process. The proposed etch recipes are specifically optimized for sub-micrometer features, and are not compatible with feature sizes in the tens of micrometer range. Based on analyzing data from our experiments and from literature, we show that a previously reported two-parameter empirical logarithmic law accurately describes the dependency of aspect ratio on trench width over a wide range of widths and etch parameters, including the sub-micrometer regime. We also propose a new figure of merit that describes the ultimate aspect ratio achievable for any given etch process.**

Index Terms— **DRIE, FIB, High aspect ratio, sub-micrometer**

I. Introduction

DEEP reactive ion etching (DRIE), initially developed for silicon-based MEMS, is gaining increasing interest in a much wider area of applications in the semiconductor industry. Besides MEMS, the other main drivers of this growth of DRIE include advanced packaging [1], power electronics [2], passive capacitive components [3], complex microfluidics devices [4], and micro-optics [5]. For most applications of DRIE, the main concern is in achieving trenches of very high aspect ratio: increasing the aspect ratio enables increasing the number of through-silicon-vias (TSVs) of a packaging layer, the electrostatic force of a MEMS actuator, and the highest achievable capacitance of a micro-machined passive component, respectively. For devices at the scale of tens of micrometers, adequate processes exist which cover the common industry needs. However, when considering sub-micrometer features, there is still a significant margin of progress that can be achieved. This is certainly the case for the above-mentioned capacitive devices [3] or for certain photonics applications, where high aspect ratio (HAR) features of quarter-wavelength width can lead to better quality Bragg mirrors [5]. HAR structures are also explored for producing thermoelectric meta-materials based on vertical superlattices [6], and highly electromagnetic-absorbent surfaces for solar cells [7]. In all these applications, the aspect ratio is the relevant figure of merit governing the ultimate performance of the devices.

On the other hand, there is no clear quantitative figure of merit which can be used to characterize the ability of a given etch process to produce HAR structures, and thus to assist the user in the selection of the most appropriate process. Usually, one of two forms of the DRIE process are used in HAR etching –the "Bosch" process, which is based on alternating depassivation, etch and repassivation steps [8], and the cryogenic process, which involves etching at temperatures typically below -100°C [9]. Both have enjoyed success at etching micrometer and sub-micrometer features to great depths. Aspect ratios of up to 107:1were reported for trenches of 374 nm widths [10]. More recently, aspect ratios of 97:1 have been reported by Owen et al [11] for trenches of 3 µm width. Other results have been published for trenches ranging from 130 nm to 2.3 µm, where aspect ratios between 30:1 and 60:1 [12, 13] were achieved.

In this manuscript, we describe optimized Bosch processes to fabricate very deep silicon trenches with aspect ratios of 160:1 for trenches of 250 nm widths, and of 124:1 for trenches of 800 nm widths respectively. Furthermore, we show preliminary results suggesting that cryogenic etch processes can be used to produce aspect ratios greater than 120:1 for 35 nm trenches. To the authors' knowledge, these are the highest values of the aspect ratio attained so far using DRIE in these dimension ranges. By combining our experiments with other reports published in the literature, we show that the dependence of aspect ratio on feature width obeys a simple two-parameter logarithmic law for a wide range of process parameters and dimensions, allowing us to propose a new figure of merit to characterize the ultimate aspect ratio that can be obtained using a specific etch process.

II. Etching experiments

Bosch process etching

The basic Bosch process is a time-multiplexed plasma etch process typically involving three distinct steps that alternate - depassivation, etch and repassivation. Some steps maybe performed concurrently. To overcome the problem of excess bowing at the top of the trenches and of narrowing at the bottom, numerous etch trials accompanied by a detailed study of the relationship between the three etch steps were performed. The best etch profile was obtained using a two-

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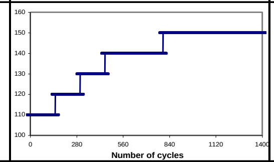
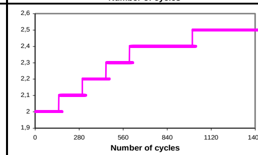
step process in which the depassivation and the etching were combined in one step. Since silicon etching takes place in this case at a lower pressure than in the regular Bosch process, this leads in a decrease of both etch rate and selectivity. Two sets of experiments were performed with the optimized Bosch process. Set 1constitutes simple trench test structures of 800 nm width, whereas Set 2 consists of trenches increasing in width from 250 nm to 5µm, with spacing of ~250nm between them. Both were fabricated on standard <100> p-doped silicon (Ultrasil – resistivity 0.01-0.015 Ω-cm). The detailed etch programs used for the two experiments are shown in Table 1, and the obtained results are represented in Figure 1. Using the Set 1 etching conditions in Table 1, 800nm-wide trenches with extremely vertical profiles and no bowing were manufactured, reaching aspect ratios as high as 124:1 (Figure 1a). As feature size decreases, achieving high aspect ratios becomes easier. Being able to achieve a ratio of 124:1 on trenches as wide as 800 nm-wide trenches is therefore a challenge, requiring dynamic adjustments of both the duration of the steps and of the plasma power for Set 1. The previous HAR record of 107:1 [10] was obtained on 374 nm-wide structures using Set 2 etch parameters, which, by extrapolating data from Figure 3, would result in an aspect ratio of approximately 80:1 if applied to 800nm structures. Using the Set 2 etch conditions in Table I, the highest aspect ratio was obtained for the 250 nm-wide trenches. The etch extended 40µm in depth, resulting in an extremely high 160:1 aspect ratio. The post-etch dicing of the samples for the purpose of SEM observation resulted in collapsed walls, as apparent in Figure 1b, however the effectiveness of etch is apparent from the regular square profile at the bottom of the trenches, which also suggests that even higher aspect ratios might be possible by further etching.

Cryogenic DRIE

By comparison with the Bosch process, cryogenic DRIE offers the benefit of producing highly vertical sidewalls with no scalloping effect, which are of great significance when etching sub-micrometer structures. This is a consequence of the process being carried out at extremely low temperatures, and results in reduced isotropic etching of silicon.

TABLE I. Parameters for deep etching of sub-micron features.

Process Parameters		Set 1	Set 2
	Source Power (W)	2800	1800
Etch + Depassivation pulse	SF6 flow (sccm)	300	300
Etch + Depassivation pulse	RF Power(W)		100
Etch + Depassivation pulse	Pulse duration (s)		5
Passivation pulse	C4F8 flow (sccm)	350	200
Passivation pulse	RF Power(W)	30	100
Passivation pulse	Pulse duration(s)	2,4	2
	Pressure (mT)	25-50	30
	Temp(°C)	10	20
	No of cycles	1400	515

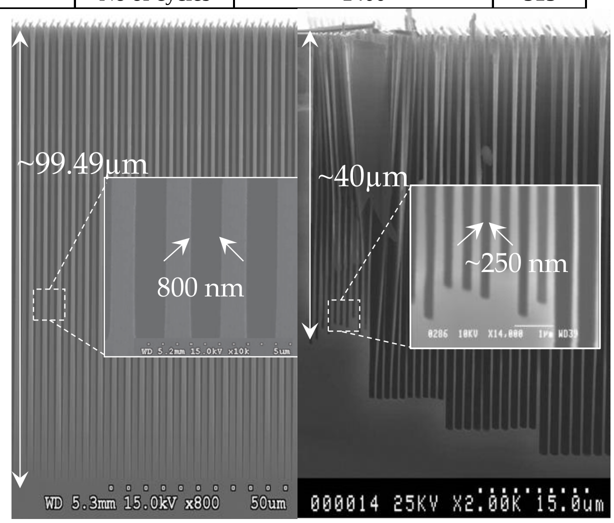


Fig. 1. HAR structures manufactured using the Bosch process: (a) 800nm-wide trenches with a depth of 99.5 µm (aspect ratio 124:1) and (b) 250nm-wide trenches with a depth of 40 µm (aspect ratio 160:1). Some of the walls collapsed during the dicing procedure.

The challenge in case of cryogenic etches is to use a suitable mask that will resist at such temperatures and that can be patterned at sub-micrometer length scales. For the final set of experiments performed in this work (Set 3), we used a combination of focused ion beam (FIB) etching and cryogenic DRIE to achieve HAR trenches with widths in the tens of nanometers range. The FIB was used to pattern lines of 35+/-10 nm width and 500 nm spacing on a 70 nm-thick aluminum film. This created a hard mask for the subsequent etching, which used the process parameters shown in Table II. Figure 2 shows the corresponding SEM results, indicating that aspect ratios of >125:1could be achieved. We also note that the FIB was used again, before the imaging, to etch a vertical rectangular hole that exposes a partial cross-sectional view of the etching. We would like to explicitly mention that these are preliminary results and that further work is ongoing.

TABLE II. Process parameters for the cryogenic etch process (Set 3).

Source Power (W)	SF6 flow (sccm)	O2 flow (sccm)	Pressure (mT)	Substrate bias (W)	Temp (°C)	Duration of etch (min)
1000	200	12	30	80	-110	10

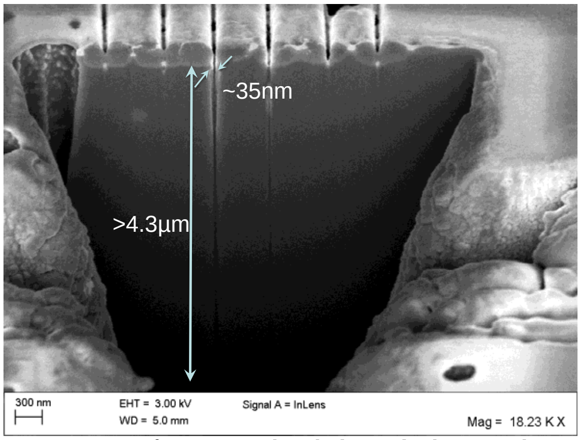


Fig. 2. SEM image of ~35nm trench etched to a depth greater than 4.3µm, hence with aspect ratio >125:1. A rectangular hole was etched using the FIB to allow cross-sectional visualization.

III. Aspect ratio versus feature size

Figure 3 shows a comparison of the aspect ratio versus feature size as studied by various groups [11-17] and updated here with our latest results. It appears that data pertaining to a particular etch process can be modeled using an empirical logarithmic law, which was previously reported [18]:

$$AR = \frac{a\log(1+b.W)}{W} \qquad (1)$$

where AR is the aspect ratio, W is width of the features (in µm), and a and b are constants with units of µm and µm^{-1} respectively, that depend on the etching process parameters. The aspect ratio, in this case, is calculated as D/W, where D is the etch depth (in µm) at the bottom of the trench. The best fit with this model was evaluated in three different cases and represented in Figure 3. The law applies over a wide dimension range. It can therefore be assumed that such trend lines can be used to reasonably predict the aspect ratios in ranges where experimental results are not available. In particular, by extrapolating the results to the limit of vanishing width W, the ultimate aspect ratio corresponding to a particular etch process can be evaluated:

$$AR_{max} = \lim_{W\to 0} \frac{a\log(1+b.W)}{W} = ab \qquad (2)$$

This ultimate aspect ratio can be calculated by performing experiments such as the Set 2 presented above, and can provide a dimension-less figure of merit for the effectiveness of a specific process to produce HAR sub-micrometer structures. For the three cases analyzed in Figure 2 we obtain the following figures of merit: 3780 for our Set 2 process from Table I, 3000 and 3240, respectively, for data previously reported in [17] and [11]. Care needs to be taken, however, on extending such extrapolation to dimensions above the micrometer range, since most processes were optimized for the sub-micrometer range. Applying such processes to larger dimensions may result in dramatic undesired results such as the formation of silicon "grass".

IV. Conclusions

Etching of sub-micrometer scale trenches was proven to give access to aspect ratios up to 124 and even 160, depending on the process parameters using both Bosch and cryogenic DRIE. The expected trend of increased aspect ratio with decreasing dimensions was experimentally validated at these scales. Furthermore, a figure of merit to evaluate the ultimate aspect ratio was proposed.

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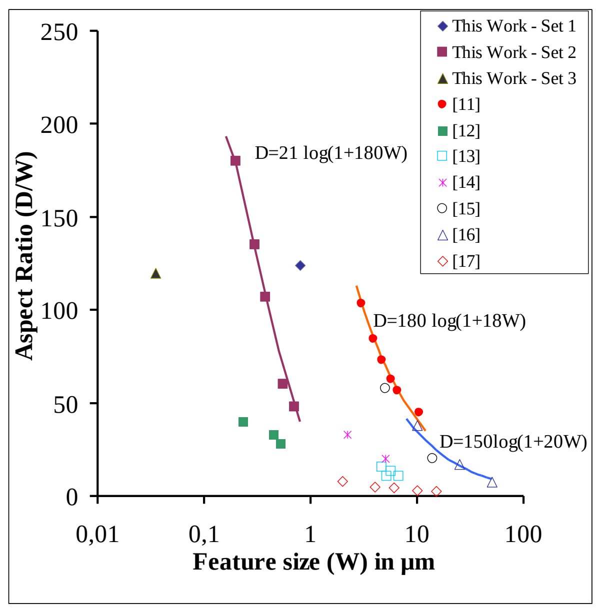

Fig. 3.Aspect ratio versus feature size as studied by various groups in the micrometer range plotted on a logarithmic scale.

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