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Deep reactive ion etching of sub-micrometer trenches with ultra high aspect ratio

Jayalakshmi Parasuraman [a], Anand Summanwar [b], Frédéric Marty [a], Philippe Basset [a], Dan E. Angelescu [a], Tarik Bourouina [a,*]

[a] Université Paris-Est, ESYCOM Lab EA 2552, ESIEE Paris, Cité Descartes-2, Bd Blaise Pascal, F-93162 Noisy-le-Grand, France
[b] SINTEF, ICT Microsystems & Nanotechnology, Gaustadalléen 23C0373, Oslo, Norway

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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 up to 120:1 on trenches of 35 nm 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 (FOM) that describes the ultimate aspect ratio achievable for any given etching process. This FOM also allows comparison of different aspect ratio performances, while taking into account in the same time, the dimension of the trench for which this performance is attained.

1. 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 on one hand, which is based on alternating depassivation, etch and repassivation steps [8], and the cryogenic process on the other hand, which involves etching at temperatures, typically below −100 °C [9]. Both have enjoyed success at etching micrometer and sub-micrometer features to great depths. Using the Bosch process, very high aspect ratio trenches have been reported in literature. Trenches with aspect ratios of up to 107:1 were reported for 374 nm widths by Marty et al. [10]. More recently, aspect ratios of 97:1 have been reported by Owen et al. [11] for trenches of 3 μm widths. 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. When considering cryogenic etching results, aspect ratios of 47.5:1 have been reported by Tillocher et al. [14] using STiGer cryoetching process.

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

* Corresponding author. Address: ESIEE Paris, Bd Blaise Pascal, Noisy le Grand 93162, France. Tel.: +33 (0) 1 4592 6692 (O); fax: +33 (0) 1 4592 6699.
E-mail address: t.bourouina@esiee.fr (T. Bourouina).

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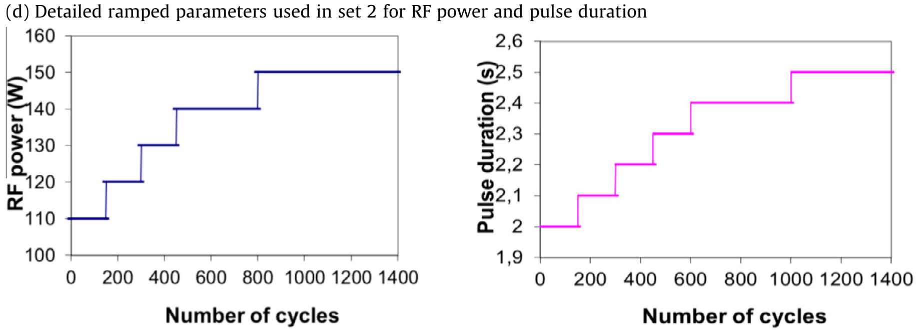
Table 1
Parameters for deep etching of sub-micron features using Bosch process (Set 1 and Set 2).

(a) General parameters	Source power (W)	Pressure (mT)	Temperature (°C)	Duration (s)	Etch rate (μm/min)
Set 1	2800	25-50	10	6610	0.90
Set 2	1800	30	20	3600	0.66
(b) Specific parameters for the passivation pulse	C_4F_8 flow (sccm)	RF power (W)		Pulse duration (s)	
Set 1	350	30		2,4	
Set 2	200	100		2	
(c) Specific parameters for the etching and depassivation pulse	SF_6 flow (sccm)	RF power (W)		Pulse duration (s)	
Set 1	300	See figure below		See figure below	
Set 2	300	100		5	

(d) Detailed ramped parameters used in set 2 for RF power and pulse duration



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. This figure of merit also allows achieving comparison of different aspect ratio performances, while taking into account in the same time, the dimension of the trench for which this performance is attained.

2. Etching experiments

2.1. 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-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. An Aluminum layer of 500 nm thickness was evaporated as a masking layer for the extremely high selectivity it offers during the DRIE process (>300:1). The etch processes were performed on an Alcatel AMS200SE machine. Set 1 constitutes simple trench test structures of 800 nm width, whereas Set 2 consists of trenches increasing in width from 250 nm to 5 μm, with spacing of ∼250 nm between them. Both were fabricated on standard <100> p-doped silicon (from 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 Fig. 1. Using the Set 1 etching conditions in Table 1, 800 nm-wide trenches with extremely vertical profiles and no bowing were manufactured, reaching aspect ratios as high as 124:1 (Fig. 1a). When considering the aspect ratio quantitatively, a decrease in feature size can lead to higher aspect ratios. Achieving an aspect 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. It is also to be noted that the DRIE process is self-limiting due to the decrease in etch rate from radical depletion described by the Knudsen transport model [15], ion depletion due to sidewall scattering, electrostatic deflection and angular distribution [16]. Yeom et al. [17] also describe a *critical aspect ratio*, corresponding to the ultimate aspect ratio that can be achieved by a process upon saturation and it turns to be no longer dependent on the etch duration. It is therefore reasonable to assume that any recipe of DRIE process has a maximum achievable aspect ratio. Using the Set 2 etch conditions in Table 1, the highest aspect ratio was obtained for the 250 nm-wide trenches. The etch extended 40 μm in depth, resulting in an extremely high aspect ratio, of 160:1. The post-etch dicing of the samples for the purpose of SEM observation resulted in collapsed walls, as apparent in Fig. 1, 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, as the saturation is not yet reached in this case.

Bosch process DRIE is also known to result in scalloping in the form of quasi-periodic sidewall roughness. Typical Bosch process surface roughnesses are in excess of 200 nm. However, when considering small trenches (in the range below 5 μm) and certainly like those used in our Set 1 & 2 experiments, this roughness drastically reduces to levels below 25 nm as roughly estimated from Fig. 1.c. This roughness eventually vanishes with increasing aspect ratios during the process, as detailed in a previous report [18],