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An advanced reactive ion etching process for very high aspect-ratio sub-micron wide trenches in silicon

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Abstract

This paper reports on a practical modification of the two-step time-multiplexed plasma etching recipe (also known as the Bosch process) to achieve high aspect-ratio sub-micron wide trenches in silicon. Mixed argon and oxygen plasma depassivation steps are introduced in between the passivation and etching phases to promote the anisotropic removal of the passivation layer at the base of the trench. Argon does not chemically react with polymers and silicon and removes the passivation layer only by physical sputtering. Therefore, it results in a highly anisotropic polymer etching process. This recipe can be easily integrated on conventional ICP equipment and the scalloping on the trench sidewall can potentially be reduced in size to less than 50 nm. To clean up all the passivation residues, a short oxygen plasma step is also added at the end of the cycle that effectively improves the uniformity of the etching profile over various opening sizes. Excellent anisotropy of the inserted argon depassivation step facilitates narrow trenches down to 130 nm wide and gap aspect-ratios as high as 40:1, extending the application of deep reactive ion etching (DRIE) processes into a new broad regime.

Keywords: DRIE; Bosch process; Anisotropic etching; Passivation layer

1. Introduction

High aspect-ratio deep reactive ion etching (DRIE) is an essential processing step that enables fabrication of many micro-electromechanical devices such as high precision motion sensors [1,2] and high performance low motional impedance capacitive resonators [3]. In these applications, the highest achievable trench aspect-ratio (depth-to-width ratio), the trench profile, and the sidewall roughness are amongst the critical process parameters. Parallel optimization of these parameters is a challenging task. For instance the time-multiplexed plasma etching recipe originally introduced in Ref. [4] and widely known as the Bosch process is an attempt to increase the anisotropy (aspect-ratio) of the silicon etching process in SF_6 plasma by protecting the trench sidewalls with a layer of a polymer deposited in between the two consecutive etching steps. The process is very successful in enabling vertical trenches with aspect-ratios as high as 30:1. However, the sidewall of a fabricated trench using the Bosch process suffers from scalloping roughness in the range of a few hundred nanometers.

To date, extensive investigations have been devoted to precise characterization and improvement of the overall performance of the Bosch process [5–9]. Recent efforts to extend the aspect-ratio limitation of the Bosch process have demonstrated a strong correlation between the tapered profile of the trench towards the bottom and insufficient removal of the polymer passivation layer [5]. To partially resolve the problem, the introduction of a separate depassivation pulse in between passivation and etching steps was suggested in Ref. [10]. This modification enables independent optimization of the depassivation process by altering the plasma gas from SF_6 to other suitable gases such as oxygen and also facilitates manipulation of the depassivation plasma parameters such as pressure, plasma density, substrate bias voltage, etc.

In this work, we have developed three- and four-pulse modified Bosch recipes on a conventional Plasma-Therm Inductively Coupled Plasma (ICP) etching tool (SLR 770). The effect of introducing oxygen and argon as depassivation gases in

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the Bosch recipe is carefully studied. We introduce a new four-pulse etching recipe that yields very high aspect-ratio deep-sub-micron trenches with uniform vertical profile for various trench widths. Argon is used in the depassivation plasma pulse to promote anisotropy of the passivation layer removal and a short oxygen-clean pulse is added to the end of each cycle that improves trench-profile uniformity by efficiently removing polymer residues. The new recipe is successfully implemented for etching deep-sub-micron gaps and the presented fabricated results show a great potential for the application of time-multiplexed DRIE processes in the single-mask fabrication of capacitively transduced MEMS devices [11].

2. Three-pulse DRIE recipe

The basic Bosch process is a time-multiplexed plasma etching process consisting of two separate steps: the etching and the passivation. The SF_6 plasma is used to etch silicon and subsequently the plasma gas is switched to C_4F_8 for a conformal coverage of the substrate surfaces with a layer of Teflon-type compound (passivation layer) that protects the sidewalls from lateral etching in the consecutive etching step (Fig. 1). Consequently, a fraction of each SF_6 etching step is dedicated to removing the passivation layer from the base of the trench and exposing silicon to reactive plasma species (fluorine radicals). This initial portion of the etching step referred to as depassivation plays a very important role in the overall performance of the process by affecting the trench profile and most importantly limiting the highest achievable aspect-ratio. As the aspect-ratio of the trench increases, effective removal of the passivation layer becomes more crucial mainly because of the decayed ion flux down to the bottom of the trench. Therefore, the trench pinches off at the bottom (Fig. 2) and after a while the etching will stop.

To enhance the passivation removal at the bottom of the trench one solution is to increase the ion flux by increasing the bias voltage [12]. However, by doing so the passivation layer on the sidewalls will be attacked by larger number of the scattered energetic ions which in turn causes appearance of excessive undercut and bowing in the trench profile. Therefore, the aspect-ratio of the Bosch process is partially limited by the anisotropy of the polymer etching step in SF_6 plasma. To further increase the aspect-ratio of the process, independent optimization of the depassivation plasma seems necessary, which calls for introduction of a third plasma pulse in between the passivation and the etching (Fig. 3).

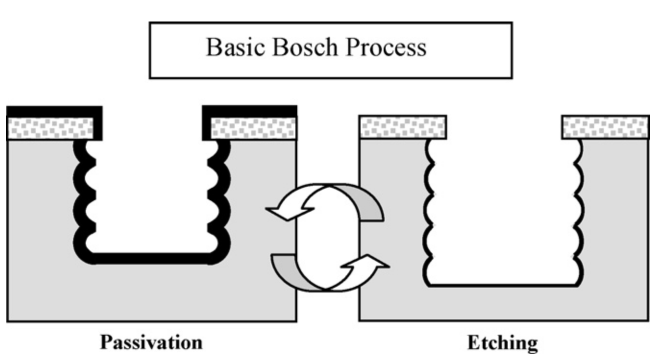

Fig. 1. Schematic viewgraph of the basic Bosch process.

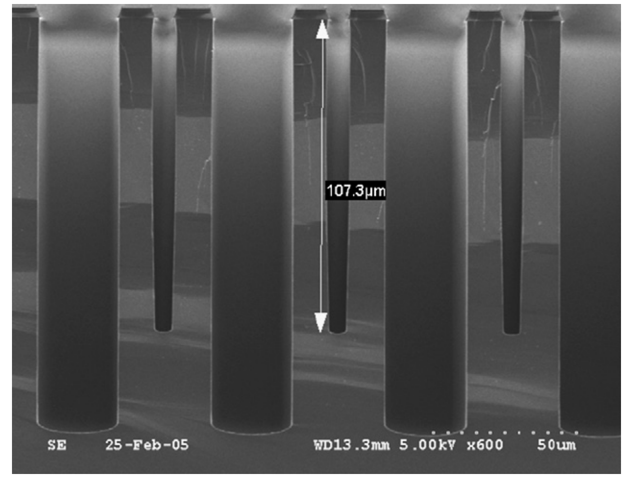

Fig. 2. SEM of trenches with two different widths demonstrating the effect of aspect ratio on the trench profile. Trenches with higher aspect ratio start to pinch-off at the bottom as a result of insufficient passivation layer removal.

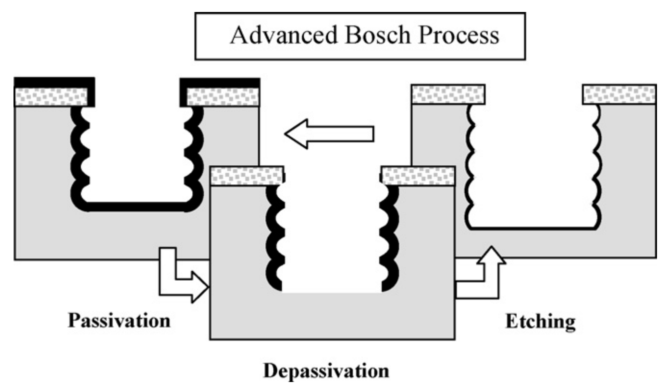

Fig. 3. Schematic viewgraph of an advanced three-pulse Bosch process.

The three-pulse recipe enables modification of the plasma parameters and the depassivation gas chemistry independent of the SF_6 etching step parameters. The application of oxygen plasma has already been suggested as depassivation plasma in Ref. [10], and is adapted by Alcatel for very high aspect-ratio (>60:1) sub-micron trench etching in silicon [13].

3. Study of three-pulse recipes by changing the depassivation gases

To evaluate the performance of the advanced three-pulse process a similar recipe is developed on a Plasma-Therm ICP tool. The depassivation gas is switched between SF_6, argon, and oxygen and the results are compared. Various trench opening sizes in a thick oxide mask are fabricated using a process explained in Ref. [11]. All the parameters for the passivation and etching steps were kept constant (Table 1) throughout the first phase of the experiment to facilitate tracking the effect of the depassivation gas on the trench profile. The etching time is reduced to 4 s to decrease the isotropic etching of silicon in each cycle and consequently suppress the scalloping roughness in an effort