Microelectronics Journal 37 (2006) 1297–1301

Microelectronics Journal

www.elsevier.com/locate/mejo

Convex corners undercutting and rhombus compensation in KOH with and without IPA solution on (1 1 0) silicon

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Received 27 April 2006; accepted 10 July 2006
Available online 30 August 2006

Abstract

The present investigation introduces convex corners undercutting and results of rhombus compensation patterns in 40% aqueous KOH solution and in KOH saturated with isopropanol (IPA) solution. All experiments are carried out on (1 1 0) silicon at 70 °C. Undercuts take place on convex corners in both solutions. Moreover, the front etch planes governing undercut vary with solutions. Rhombus compensations are used to correct the undercut. Perfect acute corner without residue is obtained, and there are only some residue structures on both sides of obtuse convex corners in KOH with IPA solution, which are better results than those in pure aqueous KOH solution.

Keywords: KOH solution; Convex corner; (1 1 0) silicon; Rhombus compensation

1. Introduction

Bulk micromachining of silicon using anisotropic wet chemical etching is one of the fundamental techniques used in the process of fabrication of microelectromechanical system (MEMS) devices. Anisotropic etching of (1 1 0) silicon is used to fabricate high-aspect-ratio stationary micro-structures and microactuators suitable for optical applications [1–4]. But, if the (1 1 0)-oriented silicon wafers are structured with convex corners, the undercutting on convex corners has been one of the obstacles to the implementation of complicated structures. From the fabrication point of view, it is especially important in etching of the structures with convex corners. Several methods for convex corners compensation techniques were investigated on (1 1 0) silicon in KOH solution [5]. Besides, the formation of silicon microstructures with convex corners by using a reoxidation process instead of compensation patterns on (1 1 0) silicon was also described [6]. The mechanism of the undercut and compensation methods in (1 1 0) silicon are not enough and widely investigated as those in (1 0 0) silicon [7–12]. Moreover, effects of adding isopropanol (IPA) to etchants are mostly studied on some special planes [13–15].

In this paper, convex corners undercutting and rhombus compensation are investigated between in aqueous KOH with and without IPA solution on (1 1 0) silicon wafers. It is demonstrated that severe undercuts exist on the corners and etch front planes vary with solution. Rhombus compensations are used to correct undercut. Results indicate that convex corners with compensation etched in aqueous KOH with IPA (KOH + IPA) solution have better results than those in pure aqueous KOH solution.

2. Convex corners undercutting

Experiments are carried out on (1 1 0) oriented *n*-type silicon wafers, double-side polished with a resisitivity of

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0026-2692/$ - see front matter
doi:10.1016/j.mejo.2006.07.008

4–6 $\Omega \cdot$cm and 290 μm thickness. Low pressure chemical vapor deposition (LPCVD) of silicon nitride 140 nm is used as an etch mask layer on (1 1 0) silicon wafers. The concentration of KOH is 40%, and solutions are in the thermostat glass vessel equipped with a stirrer and reflux condenser. The temperature inside the vessel is 70 °C. Etching rates are 0.85 μm $\min^{-1}$ for (1 1 0) surface, 0.02 μm $\min^{-1}$ for {1 1 1} planes in KOH saturated with IPA solution and 1.28 um $\min^{-1}$ for (1 1 0) plane, 0.01 um $\min^{-1}$ for {1 1 1} planes in pure aqueous KOH solution based on measurements of etched cavities with an optical microscope on (1 1 0) silicon substrates. {1 1 1} planes have the lowest etching rate both in 40% aqueous KOH solution and in KOH + IPA solution.

A parallelogram mask without compensation is used to study the undercut of convex corners on (1 1 0) silicon. Firstly, accurate crystallographic alignment with the direction of {1 1 1} planes is required. After etched for 1 h, the parallelogrammic mesa defined by four {1 1 1} planes perpendicular oriented to the (1 1 0) silicon surface are obtained. The {1 1 1} planes intersect each other with typical angle of 70.53° or 109.47°. From the scanning electron microscope (SEM) shown in Fig. 1, it can be observed that severe undercuts occur on convex corners in both solutions. The mechanism of the convex corners undercutting in (1 1 0) silicon has been presented based on the theory of covalent bond density in our previous paper [16]. Meanwhile, the formed undercut structures are different whether on obtuse convex corner or on acute convex corner. Sloping etch front planes governing the undercut are {3 1 1} and {7 7 1} crystal planes for obtuse and acute corner, respectively, in pure aqueous KOH solution [5]. Undercut structures in KOH + IPA solution are different from those in KOH solution. It has been proved that IPA can effectively reduce the etching rate of (hhl)-type planes, and cannot do so for (hll)-type planes by etching different Si {hkl} surface in pure KOH and KOH + IPA solutions [15]. So the etch rate of the {7 7 1} planes are reduced with IPA addition to KOH solution. During the process of acute corner undercutting, sloping {1 1 1} planes with an angle of 35.26° to (1 1 0) silicon surface and {7 7 1} planes emerge simultaneously. In KOH + IPA solution, front etch planes on obtuse corner are measured at an angle of about 20° with near {1 1 1} planes. Fastest etching planes take place in the ⟨3 1 1⟩ and ⟨2 2 1⟩ directions, depending on the composition of the etching solution. Moreover, this front etch planes are vertical to (1 1 0) surface plane. {2 1 1} planes can be best match with them.

3. Rhombus compensation and results

Rhombus compensation method is applied in both solutions. Fig. 2 is the schematic drawing of mask with rhombus compensation patterns. The sides are all in the direction of {1 1 1} planes perpendicular to (1 1 0) surface plane and intersect each other at the surface at angle of 70.53° or 109.47°. Relations between rhombus compensation mask dimensions, etching times and etching rates were formulated by the etching mechanism in KOH solution [5].

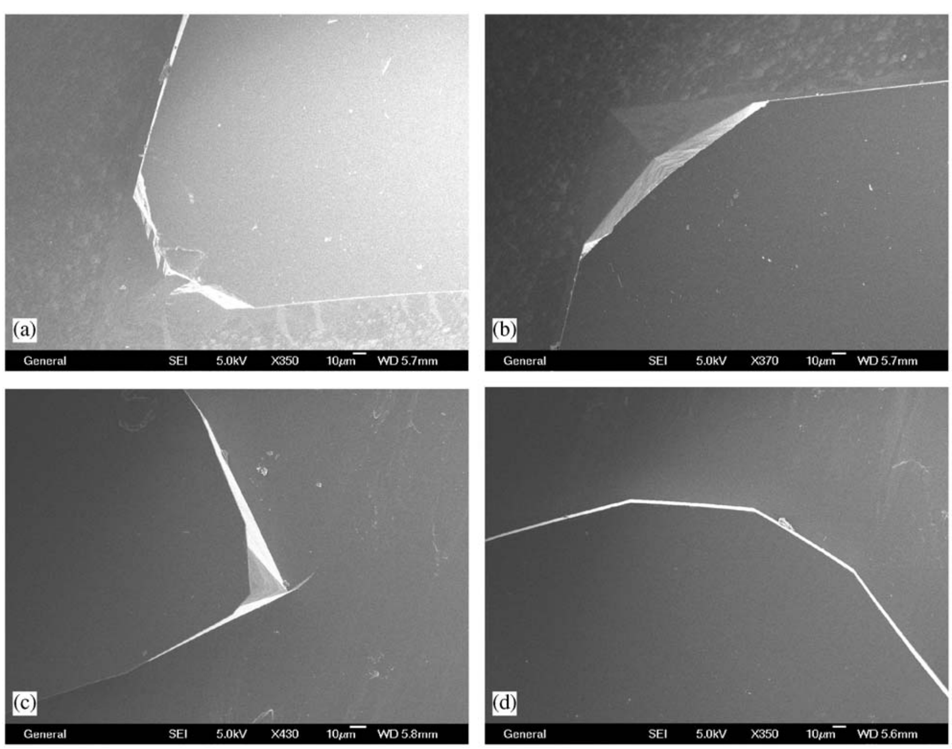

Fig. 1. Convex corners undercut: (a) acute corner in KOH solution; (b) obtuse corner in KOH solution; (c) acute corner in KOH + IPA solution; (d) obtuse corner in KOH + IPA solution.

Relations are derived only to calculate corner compensation mask for different needs. The criterion in calculating their dimensions is that the receding peak of the convex corner under the compensating patterns must reach the main mesa tip simultaneously when the specified etched height is reached. However, if etching continues, corner undercutting will start again. Equations of dimensions of rhombus compensation can be simplified as follows:

$$L_1 = R_1 \times \frac{d_{\text{depth}}}{R_{110}}, \quad L_2 = R_1 \times \frac{d_{\text{depth}}}{R_{110}},$$

where R_1, R_2 are functions of etch front planes on the corners, R_1, R_2 are different according to the etchants and the etch conditions (temperature, concentration). d_{depth} is the depth of etching (1 1 0) surface, R_{110} is the etching rate of (1 1 0) plane, so d_{depth}/R_{110} is the etching time. The length of rhombus L_1 is 110 μm and L_2 is 120 μm in these experiments. After sufficient etching has occurred, the final results are demonstrated in Fig. 3. Rhombus compensation patterns are etched away to reach the main mesa tip. Maintaining the relatively sharp features at the top, but unacceptably large residue structures remain at the bottom of both acute and obtuse corners in pure aqueous KOH solution. Even if etching continues, residues could not be etched away completely; however, corner undercutting will start again. Fig. 3(c) shows an acute corner that has much sharper profiles without residue achieved in KOH + IPA solution. But some residue structures are formed on both sides of the obtuse convex corners, and the residue structures are irregular in shape as shown in Fig. 3(d). All in all, corners with rhombus compensation etched in the KOH + IPA solution have better results compared with those in pure aqueous KOH solution. Especially, the perfect acute corner without residue can be achieved in KOH + IPA solution.

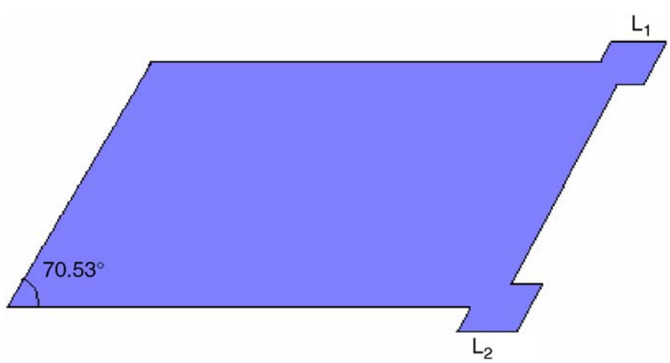

Fig. 2. Schematic view of mask with rhombic compensation patterns.

4. Discussion

Fig. 4 illustrates the regular octahedron consisting of all crystallographic {1 1 1} planes on convex corners with rhombus compensations. The $(1\,\bar{1}\,\bar{1})$ $(1\,\bar{1}\,1)$ $(\bar{1}\,1\,1)$ and $(\bar{1}\,1\,\bar{1})$ planes are perpendicular to (1 1 0) surface plane, the other four {1 1 1} planes which are $(1\,1\,\bar{1})$, (1 1 1), $(\bar{1}\,\bar{1}\,1)$ and $(\bar{1}\,\bar{1}\,\bar{1})$ planes intersect the (1 1 0) plane at an angle of 35.26°. The broken lines indicate an acute corner of the {1 1 1} planes intersecting with surface at an angle of 70.53° in Fig. 4(a) and an obtuse corner of 109.47° in Fig. 4(b).

During the process of etching away the rhombus compensation patterns on convex corners, the slow etching

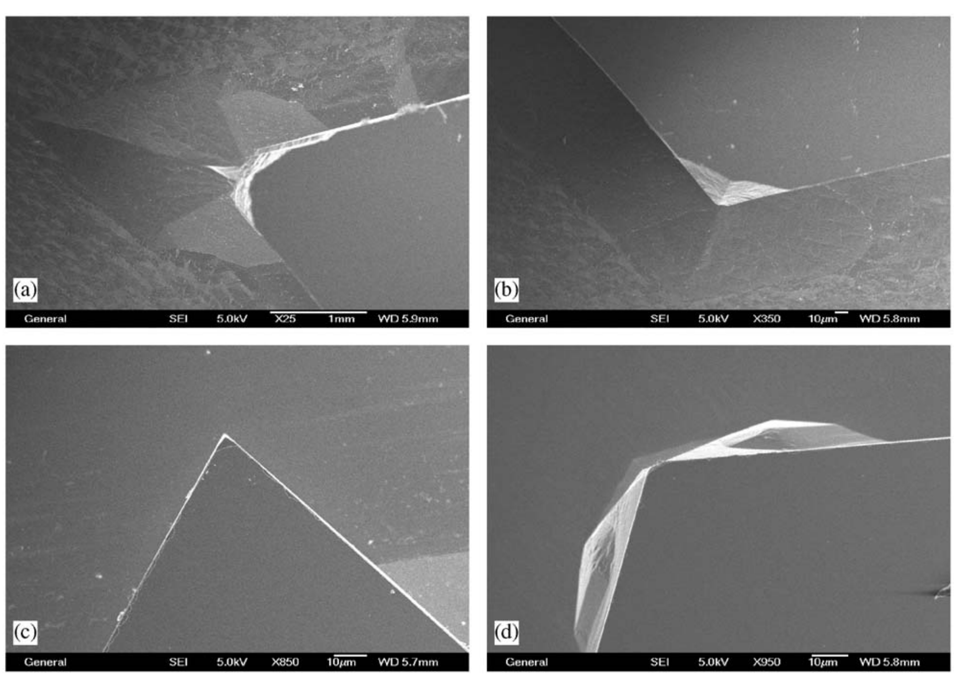

Fig. 3. Results of corners with rhombus compensation: (a) acute corner in KOH solution; (b) obtuse corner in KOH solution; (c) acute corner in KOH + IPA solution; (d) obtuse corner in KOH + IPA solution.

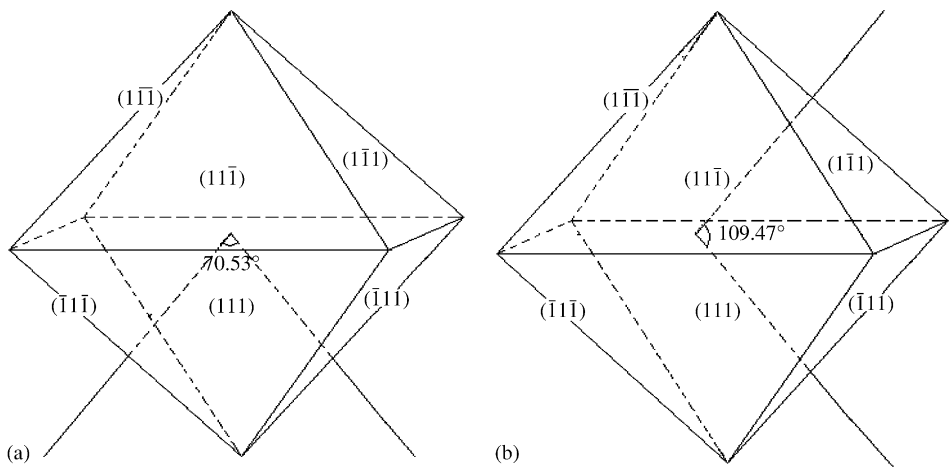

Fig. 4. Regular octahedron consisting of all crystallographic {1 1 1} planes on convex corners with rhombus compensation: (a) acute corner; (b) obtuse corner.

{1 1 1} planes on the corners can be illustrated in Fig. 4. Fast etch front planes govern the intersection of these {1 1 1} planes during undercut. To compensate undercut of the acute corner, two obtuse corners of the rhombus compensation patterns must undercut completely. In pure aqueous KOH solution, the fast etching {3 1 1} and {7 7 1} planes sloping with (1 1 0) surface plane form the residues on the acute corner after etching the compensation structure. In KOH + IPA solution, {2 1 1} planes emerge on obtuse corner during undercut. Moreover, the etch rate of {7 7 1} planes on acute corner is reduced with the IPA addition to the solutions. Rhombus compensation on acute corner can be entirely consumed until the front etching encounters the slow etching vertical {1 1 1} planes. In the end the perfect acute convex corner is formed.

Rhombus compensation mechanism on obtuse corners is similar to that on acute corner. Two acute corners of rhombic compensation pattern must undercut away. In KOH solution, the fast etching {3 1 1} and {7 7 1} planes also form the residues on the obtuse corner. But in KOH + IPA solution, the {1 1 1} planes tending towards the surface at an angle of 35.26° and {7 7 1} planes are developed simultaneously when the acute convex corner undercuts. The existence of slow etching {1 1 1} planes and {7 7 1}planes arranged towards the surface at an angle as well as other fast etching planes lead to the residues on the obtuse corner. Etch rate of {1 1 1} planes is much slower than that of any other orientation planes. So {1 1 1} planes will not be etched away easily. These low etching {1 1 1} planes are one of the major crystal planes forming the residues structure.

5. Conclusion

Study and experiments of convex corners undercutting and rhombus compensation patterns on (1 1 0) silicon are presented comparatively between in aqueous KOH with and without IPA solution. Undercuts exist on the corners during etching in both solutions. Front etch planes governing undercut are all given. The front etch planes are {3 1 1} and {7 7 1} crystal planes for obtuse and acute corner, respectively, in pure KOH solution. In KOH + IPA solution, sloping {1 1 1} planes with an angle of 35.26° to the (1 1 0) silicon surface and the fast etching {7 7 1} planes emerge simultaneously on acute corner during undercut. The front etch planes on obtuse corner are {2 1 1} planes vertical to (1 1 0) surface plane. Rhombus compensation patterns are used in the mask to prevent undercut in two solutions. The large residue structures emerge whether on obtuse convex corners or on acute convex corners in aqueous KOH solution. However, perfect acute convex corner is achieved and irregular residues emerge on both sides of obtuse corner in KOH + IPA solution. Different results are caused by the etching mechanism depending on the composition of the etching solutions.

Acknowledgements

This work was supported by Science Development Plan Foundation of Jilin Province, China (Grant no. 20050319).

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