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Micromirrors inclined at 45° towards Si substrates fabricated by anisotropic etching

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A study of manufacturing micromirrors inclined at 45° towards silicon substrate has been presented in this paper. The micromirrors can be formed by {100} or {110} sidewall planes etched in (110) or (100) Si substrates in alkaline solutions. The smoothness of the surface and etch rate anisotropy are crucial parameters of fabricated structures. The research focused on Si(100) wafers etched either in KOH solutions with alcohol additives or in low concentrated TMAH solutions with surfactant addition and on Si(110) wafers etched in pure highly concentrated KOH or TMAH solutions. The examination showed difficulty of fabrication of the structures with smooth sidewalls and with appropriate shape simultaneously. At the end of the paper, the structure for bringing close and parallel of two optical beams has been proposed.

Keywords: micro-opto-electro-mechanical systems (MOEMS), micromirrors, silicon anisotropic etching.

1. Introduction

Silicon spatial structures etched in alkaline solutions are of special interest in the field of micro-opto-electro-mechanical systems (MOEMS), due to the simplicity and relatively low cost of fabricating the structures with desirable parameters. Selecting a composition of the etching solution, geometry of the etching mask and crystallographic orientation of the Si substrate enables one to shape easily three-dimensional structures with required shapes. Micromirrors are one of possible applications of smooth sidewalls of the etched structures [1, 2]. Surface roughness and the angle of inclination towards the substrate are essential parameters of the sidewalls forming the micromirrors.

Shaping spatial structures by silicon anisotropic etching in alkaline solutions allows one to take advantage of natural arrangement of Si(*hkl*) planes. The angle between two crystallographic planes {100} and {110} in a regular crystal, like for instance silicon, is exactly 45°. The structures bounded by the sidewalls inclined to the substrate at an angle of 45° can be used for changing the direction of light beam propagation of an angle of 90°. Such structures can be obtained either by forming

{110} sidewalls on (100) substrate or by forming {100} sidewalls on (110) substrate. In both cases an appropriate mask pattern should be designed. Its arrangement on Si substrate should be based on stereographic projection. The pattern design should take into account the mask underetching.

While designing the mask, one must know the etch rates of the substrate and the planes forming the sidewalls of etched structure. The knowledge of the morphology of the planes after etching is important, too. The etching solution should be selected from the point of view of a desirable etch rate anisotropy and a high smoothness of the planes forming the structure, especially the sidewalls. In this work, we have investigated the structures bounded by {110} or {100} sidewall planes etched in Si(100) or Si(110) substrates in KOH and TMAH (tetramethylammonium hydroxide) solutions with or without additives. We have also proposed a structure for bringing close and parallel of two light beams.

2. Study of the structures employing {100} and {110} planes

2.1. Structures etched in (100) substrate

The structures etched in the most common Si(100) substrate usually use the slowest etched {111} planes. However, the angle made between {100} and {111} planes is 54.74°, what makes the usage of {111} planes useless from the point of view of our application. To obtain an angle of 45°, the sidewalls have to be formed by {110} planes. This requires setting the edges of the etching mask perpendicularly to ⟨100⟩ directions. While designing the mask, it is convenient to use the stereographic projection on {100} plane (Fig. 1**a**). The arrangement of the mask in relation to ⟨100⟩ directions has been marked with a dashed line.

The {110} sidewall planes are achievable in KOH solutions with alcohols addition or in low concentrated TMAH solutions, optionally with surfactants addition [3, 4].

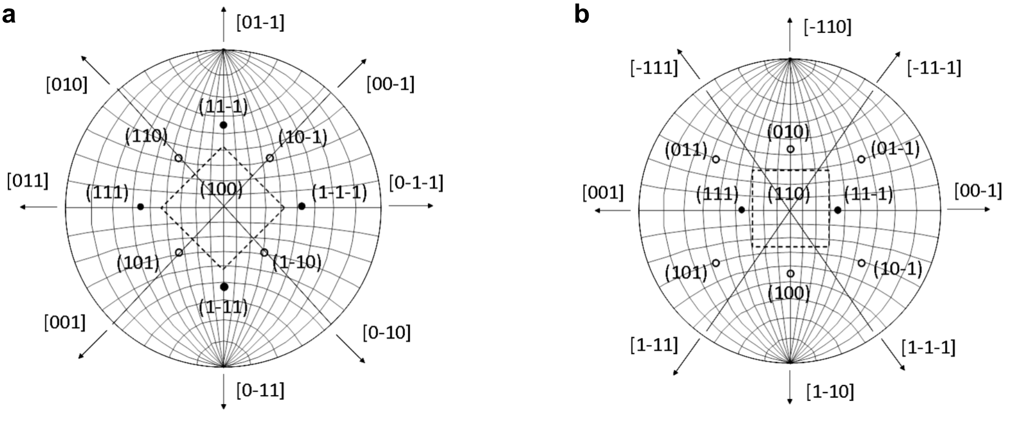

Fig. 1. Stereographic projection on {100} plane (**a**), and {110} plane (**b**). The arrangement of the etching masks in relation to crystallographic directions has been marked with a dashed line.

In these solutions, {110} plane is the plane with the lowest etch rate in ⟨100⟩ direction (what means that it is etched slower than {100} plane) and, in consequence, it forms the sidewall of the etched structure. To acquire a desirable shape of the structure, the $V_{(110)}/V_{(100)}$ etch rate ratio should be not only lower than one, but also as low as it is possible. Otherwise, after long enough time of etching, the {110} sidewall planes might be replaced by the {111} facets, which are the slowest etched planes of all.

The etching process was carried out in 3 M KOH solutions saturated with 1-propanol, 2-propanol, isobutanol and *tert*-butanol as well as in 10% and 5% TMAH solutions with the addition of 150 ppm of Triton X-100. In all these solutions, the etch rate of (110) plane was expected to be lower than the etch rate of (100) plane. The experiment was conducted at the temperature of 75 °C, at atmospheric pressure. The etch rate of (100) plane was estimated by the etching depth measurement with a micrometric tool within the accuracy of 0.5 μm. The etch rate of (110) plane was evaluated by the measurement of underetching of SiO_2 mask with an optical microscope. The acquired etch rate results are presented in Tab. 1 and Fig. 2.

Table 1. Etch rate results in various solutions.

Solution	(100) etch rate [μm/min]	(110) etch rate [μm/min]
1. 3 M KOH + 1-propanol	0.54	0.16
2. 3 M KOH + 2-propanol	0.59	0.12
3. 3 M KOH + isobutanol	0.16	0.10
4. 3 M KOH + *tert*-butanol	0.31	0.08
5. 10% TMAH + Triton X-100	0.07	0.04
6. 5% TMAH + Triton X-100	0.03	0.02

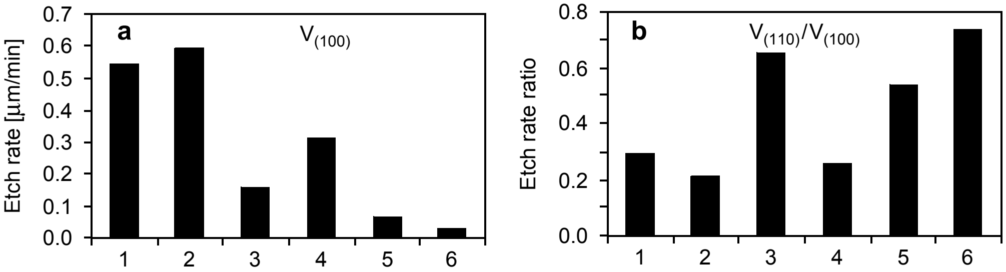

Fig. 2. Etch rates of (100) plane (**a**) and $V_{(110)}/V_{(100)}$ etch rate ratio in various solutions (**b**). The numbers refer to the solutions in Tab. 1.

The (100) plane is etched relatively slowly in the TMAH solutions with Triton addition. The $V_{(110)}/V_{(100)}$ etch rate ratio is distinctly lower in the solutions with alcohols (except for isobutanol) than in the TMAH + Triton solutions. The highest etch rate of (100) plane as well as the lowest $V_{(110)}/V_{(100)}$ etch rate ratio is in the solution with isopropanol (2-propanol).

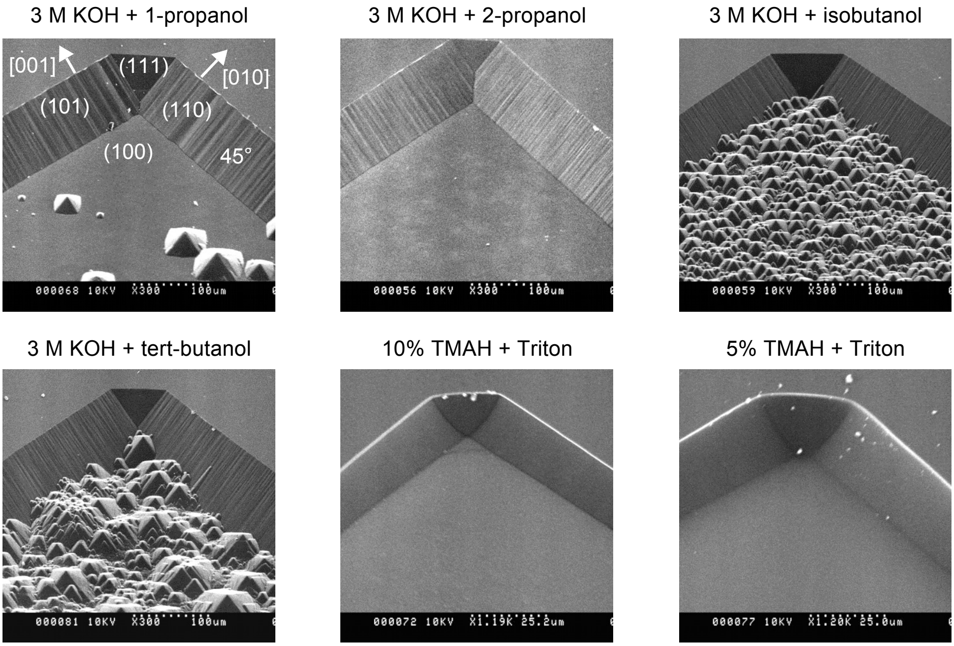
3 M KOH + 1-propanol
3 M KOH + 2-propanol
3 M KOH + isobutanol
3 M KOH + tert-butanol
10% TMAH + Triton
5% TMAH + Triton

Fig. 3. SEM images of the structures etched on Si(100) substrate through the mask perpendicular to ⟨100⟩ direction in various alkaline solutions.

SEM images of the etched structures are presented in Fig. 3. The surfaces of the (100) substrates etched in the solutions with butyl alcohols are densely covered by hillocks, contrary to the surfaces etched in the solutions with propyl alcohols. Although there are individual hillocks on (100) plane etched in the solution with 1-propanol, they do not occur on the plane etched in the solution with 2-propanol. The sidewalls (formed by {110} planes) of the etched structures are patterned with stripes for each of the solutions with alcohol additives.

In case of the both TMAH with Triton solutions, the sidewalls formed by {110} planes as well as the surfaces of the (100) substrates are very smooth. However, despite the low etching depth, due to the high value of $V_{(110)}/V_{(100)}$ etch rate ratio and the low etch rate of (100) plane, the (111) plane is widely developed. This would lead to the decline of the {110} planes in favor of {111} planes, if the structure was etched several times deeper.

On the one hand, the etch rate anisotropy (described by $V_{(110)}/V_{(100)}$ etch rate ratio) is better for the most of KOH solutions with alcohols, especially with isopropanol. On the other hand, the surfaces of the structures etched in the TMAH with Triton solutions are considerably smoother. The ideal structure should take advantage of etch rate anisotropy of the KOH solutions with alcohols and the good quality of surfaces etched in the TMAH + Triton solutions.

2.2. Structures etched in (110) substrate

In the case of Si(110) substrates, the sidewalls inclined towards the substrate at 45° can be formed by {100} planes. The {100} sidewall planes are achievable in pure highly concentrated KOH or TMAH water solutions when the edges of the etching mask are set perpendicularly to ⟨110⟩ directions. The {100} plane is the slowest etched plane in ⟨110⟩ direction in the mentioned solutions and, as a result of setting the mask, forms a sidewall of the etched structure.

Similarly to structures fabricated in (100) substrate, the stereographic projection can be applied to designing the etching mask on (110) substrate (Fig. 1**b**). Opposite to the structure etched in (100) substrate, $V_{(110)}/V_{(100)}$ etch rate ratio in the case of the structure formed on (110) substrate should be distinctly higher than one. This ensures that {100} plane develops instead of {110} one and is not replaced at all by the slowest etched {111} plane.

The experiment was conducted in 10 M KOH solution at the temperature of 80 °C and in 25% TMAH solution at 90 °C, both at atmospheric pressure. The etch rates of the substrate and the sidewall plane were evaluated by the same methods as for structures fabricated in (100) substrate. The acquired results are shown in Tab. 2 and Fig. 4.

The etch rate as well as the $V_{(110)}/V_{(100)}$ etch rate ratio in the KOH solution is higher than in the TMAH one. The (100) sidewall plane seems to be smooth after etching in

Table 2. Etch rate results in two different solutions.

Solution	(110) etch rate [μm/min]	(100) etch rate [μm/min]	$V_{(110)}/V_{(100)}$ etch rate ratio
10 M KOH	1.4	0.64	2.2
25% TMAH	1.07	0.59	1.8

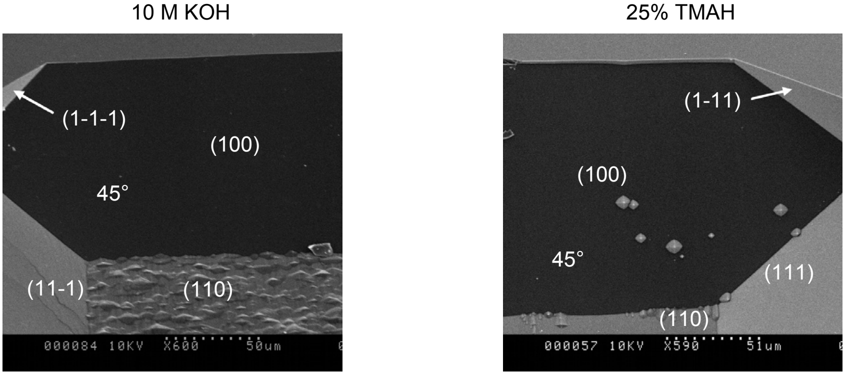

Fig. 4. SEM images of the structures etched in Si(110) substrate through the mask perpendicular to ⟨110⟩ direction in KOH and TMAH solutions.

the KOH solution, while the plane etched in the TMAH solution is covered by individual hillocks. These results suggest that highly concentrated KOH solution is more applicable to the fabrication of the structures in (110) substrate with the {100} sidewall planes forming micromirrors.

3. Example of micromirrors realization

The presented study of anisotropic etching of silicon structures with the sidewalls inclined towards substrate at an angle of 45° has been conducted due to their possible application for micromirrors. The structures with the sidewalls forming the mirrors for bringing close two optical beams have been designed. They employ Si substrates with (100) and (110) orientations. The structure (Fig. 5) can serve as a waveguide, reflecting the light beams parallel to the substrate plane, at the angle of 90°.

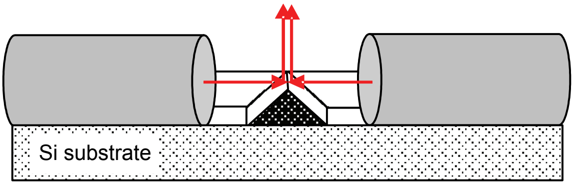

Fig. 5. The idea of the structure for interference of two parallel light beams.

The structures were manufactured based on the research discussed in Section 2. The structure in (100) substrate was etched in 3 M KOH solution saturated with isopropanol, while the structure in (110) substrate was etched in 10 M KOH solution. The structure fabricated in (100) substrate is presented in Fig. 6. The edge between two {110} planes forming the mirrors is almost sharp. Although the structure has a desirable shape, the mirror formed by {110} plane is patterned with stripes. In case of (110) substrate, the time of etching necessary for achieving V-groove formed

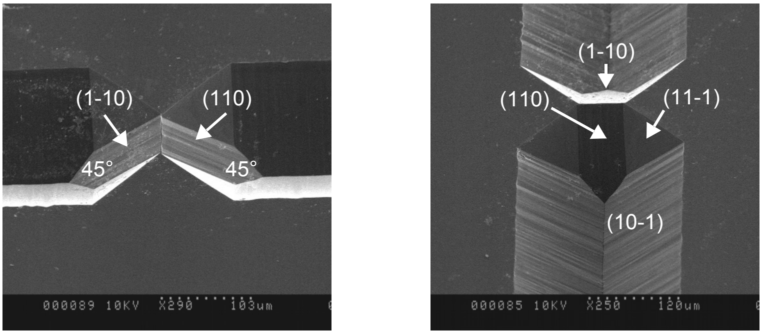

Fig. 6. SEM images of the structure etched in Si(100) substrate in 3 M KOH with isopropanol solution.

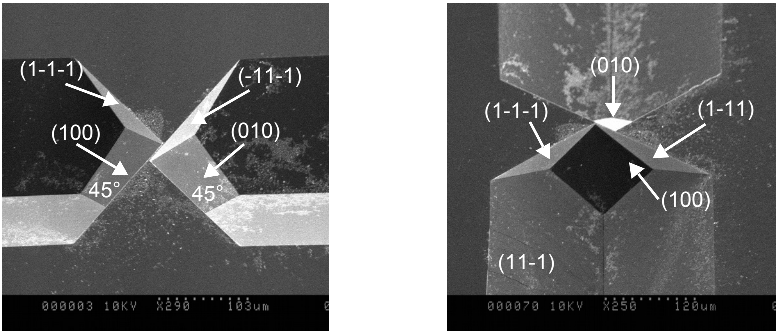

Fig. 7. SEM images of the structure etched in Si(110) substrate in 10 M KOH solution.

by {111} planes was so long that a part of {100} sidewall plane was replaced by {111} planes (Fig. 7). Thus, in spite of the smooth mirror formed by {100} plane, the etch rate anisotropy makes achieving required shapes of the structure difficult.

4. Conclusions

The fabrication of micromirrors inclined at 45° towards the substrate by anisotropic etching of Si(100) and Si(110) wafers has been investigated. The process was carried out in KOH and TMAH solutions with and without alcohols or surfactant addition. The {110} micromirror sidewall planes developed during the etching of Si(100) substrates in KOH solutions with alcohols were patterned with stripes, whereas these sidewall planes etched in TMAH solutions with Triton X-100 surfactant turned out to be smooth. However, the etch rate anisotropy was generally superior in KOH solutions with alcohols, especially with isopropanol. In case of Si(110) substrates, the etch rate anisotropy as well as the smoothness of the {100} micromirror sidewall planes in the KOH solution was better than in the TMAH one.

The structure with micromirrors for bringing close and parallel two light beams has been designed. Basing on the conducted research, the etching solutions for fabricating sidewall planes forming micromirrors have been selected. The structure in Si(100) substrate was fabricated in KOH with isopropanol solution, while the structure in Si(110) was manufactured in pure highly concentrated KOH solution. Although the {100} micromirror planes in Si(110) substrate were smooth, the shape of the structure was not satisfactory. Despite the appropriate shape of the structure fabricated in the Si(100) substrate, the {110} sidewall planes were not smooth enough.

The acquired results indicate that the study on etching anisotropy and surface smoothness of silicon structures etched in various alkaline solutions should be continued. The examination ought to be focused on the search for the composition of etching solution, which will enable one to fabricate structures with smooth micromirror sidewall planes and with desirable shapes. The sidewalls of the fabricated structures should be tested from the point of view of their optical properties, too. This will be the subject of our further investigation.

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