Precise identification of ⟨100⟩ directions on Si{001} wafer using a novel self-aligning pre-etched technique

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Abstract. Micromirrors with tilt angle of 45° are widely used in optical switching and interconnect applications which require 90° out of plane reflection. Silicon wet bulk micromachining based on surfactant added TMAH is usually employed to fabricate 45° slanted walls at ⟨100⟩ direction on Si{001} wafers. These slanted walls are used as 45° micromirrors. However, the appearance of precise 45° {011} wall is subject to the accurate identification of ⟨100⟩ direction. In this paper, we present a simple technique based on pre-etched patterns for the identification of ⟨100⟩ directions on Si{001} surface. The proposed pre-etched pattern self-aligns itself at the ⟨100⟩ direction while getting misaligned at other directions. The ⟨100⟩ direction is determined by simple visual inspection of pre-etched patterns and does not need any kind of measurement. To test the accuracy of the proposed method, we fabricated a 32 mm long rectangular opening with the sides aligned along the ⟨100⟩ direction which is determined using the proposed technique. Due to finite etch rate of {110} plane, undercutting occurred, which was measured at 12 different locations along the longer edge of rectangular strip. The mean of these undercutting lengths, measured perpendicular to the mask edge is found to be 13.41 μm with a sub-micron standard deviation of 0.38 μm. Such level of uniform undercutting indicates that our method to identify the ⟨100⟩ direction is precise and accurate. The developed method will be extremely useful in fabricating arrays of 45° micromirrors.

Keywords: Pre-etched Patterns, Crystallographic Directions, Wet Etching

1. Introduction

Wet bulk micromachining is the most appropriate technique to fabricate microstructures with slanted sidewalls. In wet anisotropic etching, the etching characteristics are highly orientation dependent [1, 2, 3, 4, 5, 6, 7]. In all kinds of anisotropic etchants, the etch rate is slowest along {111} planes. However, the relative etch rates of other planes such as {100} and {110} can be altered significantly by the addition of a small amount of surfactant, especially, high concentration TMAH (e.g. 20-25 wt%) [8, 9, 10, 11, 12, 13, 14, 15]. In surfactant added 25 wt% TMAH, the etch rate of {110} planes is reduced significantly while that of {100} plane remains almost unaltered [8, 9, 10, 11, 12, 13, 16]. At the same time the undercutting at convex corners on Si{100} surface is suppressed when surfactant is added in TMAH solution [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]. These etching characteristics are exploited to fabricate mesa structures, bent V-grooves, proof mass for accelerometer etc. [19, 20, 21, 22]. Additionally, it is also used to fabricate 45^o micromirrors which are used in optical MEMS to provide 90^o out-of-plane reflection as illustrated in figure 1. In order to ensure that the reflected beam is exactly perpendicular to the incoming beam as shown in figure 1, it is vital to ensure that the mirror walls are precisely at an angle of 45^o. On Si{001} wafer, {011} plane oriented at an angle of 45^o to the wafer surface appear at the ⟨100⟩ direction. The surfactant added TMAH provides high etching selectivity between {100} and {110} planes and therefore, it is exploited for the fabrication of 45^o micromirrors [23, 24, 25]. In order to achieve smooth and exactly 45^o sidewall, the mask edges must be precisely aligned along ⟨100⟩ direction on Si{001} surface. Therefore, an accurate identification of ⟨100⟩ direction is the first step in order to fabricate a mirror with accurate functionality. Since, the wafer flat usually has an inaccuracy of 1-5^o, we cannot rely on the wafer flat for aligning our mask pattern in the cases where dimensionally accurate structures are required [26]. Another method to determine the crystallographic directions is the X-ray diffraction, which is very difficult to mount with mask aligner. Therefore, anisotropically wet etched patterns, which are called pre-etched patterns, are most widely used to determine the correct directions [26, 27, 28, 29, 30, 31, 32]. In general, pre-etched patterns are fabricated on the wafer prior to the lithography of the required structure. These patterns when etched, provide an alignment aid for the subsequent lithography steps for the alignment of mask edges along required crystallographic directions.

Researchers have proposed different pre-etched patterns to determine the crystallographic directions with varying accuracy. Ensell [30] used a series of circular openings to determine the ⟨110⟩ direction on Si{001} wafer with an accuracy of 0.1^o. Lai *et al* used a repeated pattern of squared and rectangular geometry to determine the ⟨110⟩ direction on Si{001} wafer with an accuracy of 0.01^o [31]. Tseng *et al* used a series of circular pre-etched patterns to determine the ⟨100⟩ direction on Si{011} wafer with a precision of 0.02^o [26]. James *et al* [32] demonstrated three methods of precise alignment on Si{110} wafer, and subsequently, they showed that etching

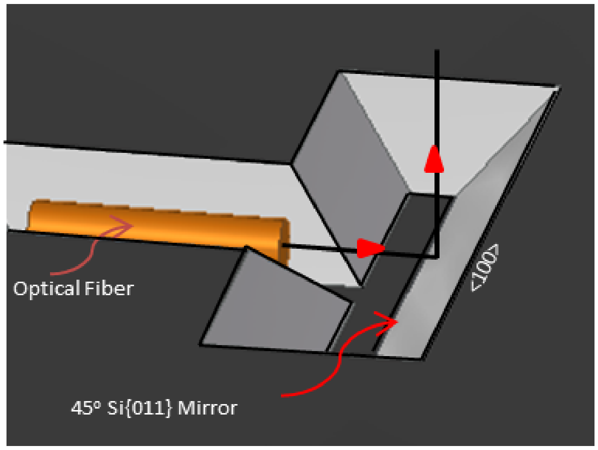

Figure 1. Schematic diagram showing the 90° out of plane reflection of a beam of light (coming from the optical fiber) from a 45° micromirror of {011} wall fabricated in Si{001} wafer.

the circular window of 1 mm diameter to obtain hexahedron and aligning its edge to a dimensionally similar hexagon on the subsequent mask gives precise alignment. However, this method is prone to theta error. On Si{001} wafer, these attempts have mostly been limited to determining the ⟨110⟩ directions. Moreover, most of these methods require the measurement of either the undercutting length or the distance between successive structures to determine the correct directions. The measurement of such small distances like 0.07 μm in case of the pattern proposed by Ensell [30] and 0.18 μm in the work done by Lai *et al* [31] not only requires sophisticated equipment but it is also prone to some inadvertent errors. On the other hand, there is a need to develop a versatile technique to determine the ⟨100⟩ directions as well, on Si{001} wafer which are essential for the fabrication of 45° micromirrors as explained above.

In this paper, we present a novel self-aligning pre-etched pattern to precisely identify the ⟨100⟩ directions on Si{001} wafers. The proposed pre-etched patterns self-aligns itself at the ⟨100⟩ direction while getting misaligned at directions away from ⟨100⟩. This self-aligned pattern distinguishes the precise ⟨100⟩ direction by making it appear quite obvious amongst the cluster of patterns. The aligned patterns can be easily located using a simple optical microscope. Additionally, the proposed technique does not require any measurement to identify correct direction.

2. Design Methodology

To demonstrate the usefulness of the present technique, we take a pattern consisting of 4 circular openings of 100 μm diameter each. They are separated by a distance of 45.5 μm, 44.5 μm, 43.4 μm from each other along the radial direction. The center of all these 4 circles lies on a straight line passing through the center of the wafer. This pattern is then repeated at an angular pitch of 0.17° on both sides of the reference line, as shown

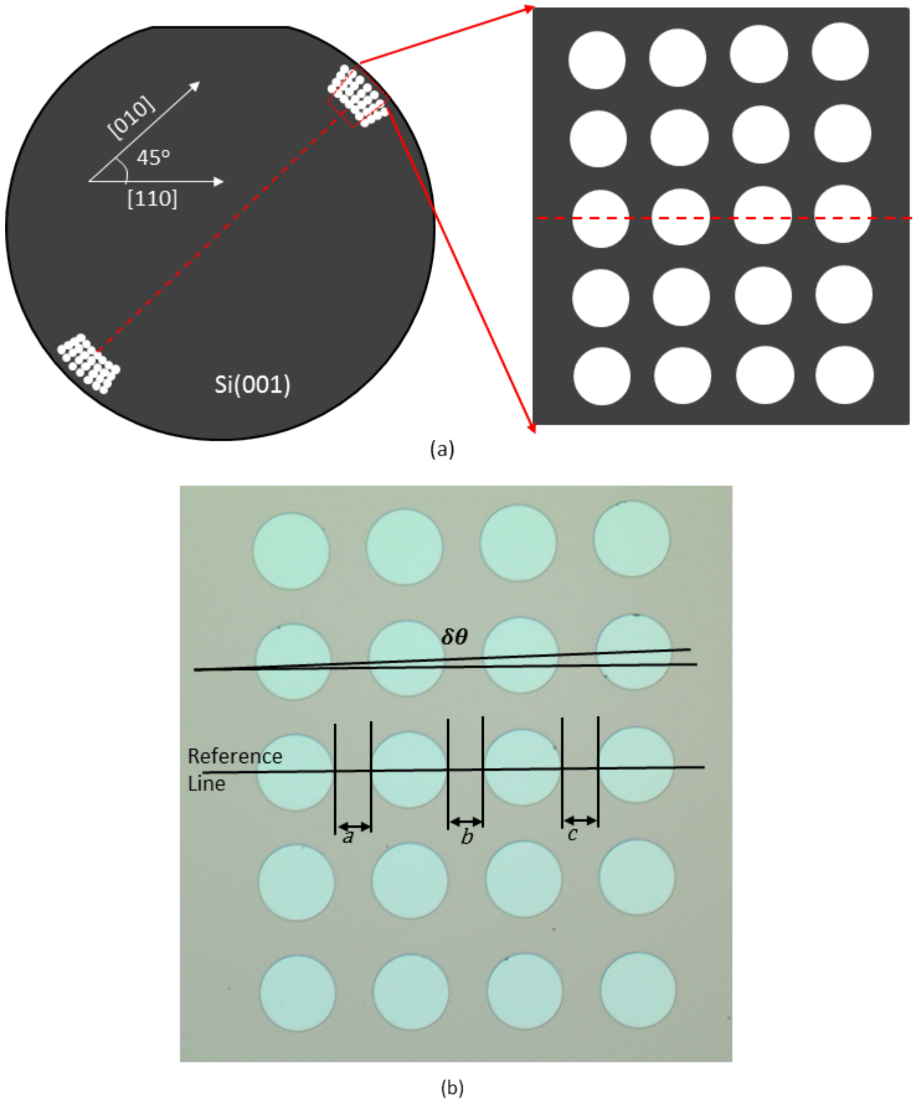

Figure 2. The proposed pre-etched patterns: (a) Schematic diagram showing the pre-etched pattern on the diametrically opposite ends of the wafer. The zoomed image shows the arrangement of the pattern. For better visualization, the dimension of the circles are increased and thus number of circles reduced from the actual pattern, in this schematic diagram. (b) Optical image of a part of the patterned geometry on silicon wafer. The dimensions and the details of the pattern can be seen from Table 1.

in figure 2. The number of circles in each row along the periphery of the wafer is 49. As a result the total number of circles in all the 4 rows is 196. It is to be noted that the same set of circles (i.e. 196 circles) are patterned on diametrically opposite side of the wafer as well. The number of circles depends on the accuracy of the wafer flat. In figure 2, the diameter of the circles are increased and thus the number of circles reduced for better visualization. The dimensions are tabulated in table 1.

During fabrication, due to prolonged etching in anisotropic etchant, the circular openings take the shape of inverted pyramids (or square V-Grooves) with {111}

Table 1. The details of the proposed pre-etched patterns

Quantity	Value
Wafer Type	Si{001}
Number of circles on each side of the wafer	49*4=196
Diameter of each circle	100 μm
(a,b,c)	(43.5,44.5,45.5) μm
$\delta\theta$	0.17^o

sidewalls. Near the perfectly aligned ⟨100⟩ directions, the radial diagonals of all the four fabricated squares will lie on one straight line passing through the center of the wafer. This will make the notches of all the 4 circles align itself at the ⟨100⟩ direction, whereas, at other directions, the notches will self-misalign from each other, consequently, the radial diagonal will not lie on a straight line. The extent of this misalignment depends on the extent of deviation from the ⟨100⟩ directions. As the ⟨100⟩ direction is approached from one side, the misalignment continue to reduce, becomes zero at the perfect ⟨100⟩ direction. The misalignment of the notches increases again, however, in the opposite direction, as we continue to move away from the ⟨100⟩ direction on the other side.

3. Experimental Methodology

The wafers used in the experiments are Cz-grown {001} oriented p-type (boron doped) with a diameter of 4 inch and resistivity in the range 1-10 Ω-cm. Thermally grown oxide layer is used as mask layer. The proposed patterns as described in the previous section and as shown schematically in figure 2 are transferred on a positive photoresist coated wafer using photolithography. Thereafter, oxide etching is carried out in buffered hydrofluoric acid (BHF). After removing the oxide at the exposed areas, i.e., the circular pre-etched patterns, photoresist is removed in acetone. Then the wafer is cleaned in piranha bath ($H_2SO_4 : H_2O_2 :: 1 : 1$) followed by a through rinse in deionized (DI) water. Etching is then carried out in 25 wt% TMAH at 70^{o}C. On prolonged etching, the circular geometry takes the shape of square cavities as shown in the optical images in figure 3. From the cluster of pre-etched patterns, we locate that set of squares whose notches align exactly to each other. This particular set of squares is used as the reference ⟨100⟩ direction. The optical image in figure 3 shows the etched circles near the perfectly aligned pattern.

In order to check the accuracy of the proposed method, a 32 mm long rectangular opening whose edges are aligned along ⟨100⟩ direction is patterned on oxidized silicon wafer. The edges of the rectangle are aligned along ⟨100⟩ direction with the help of pre-etched patterns. This long rectangular opening is subsequently etched in TMAH+0.1% Triton to expose Si{011} sidewalls at ⟨100⟩ mask edges. The undercutting perpendicular to the mask edge of the rectangle is measured using optical microscope.

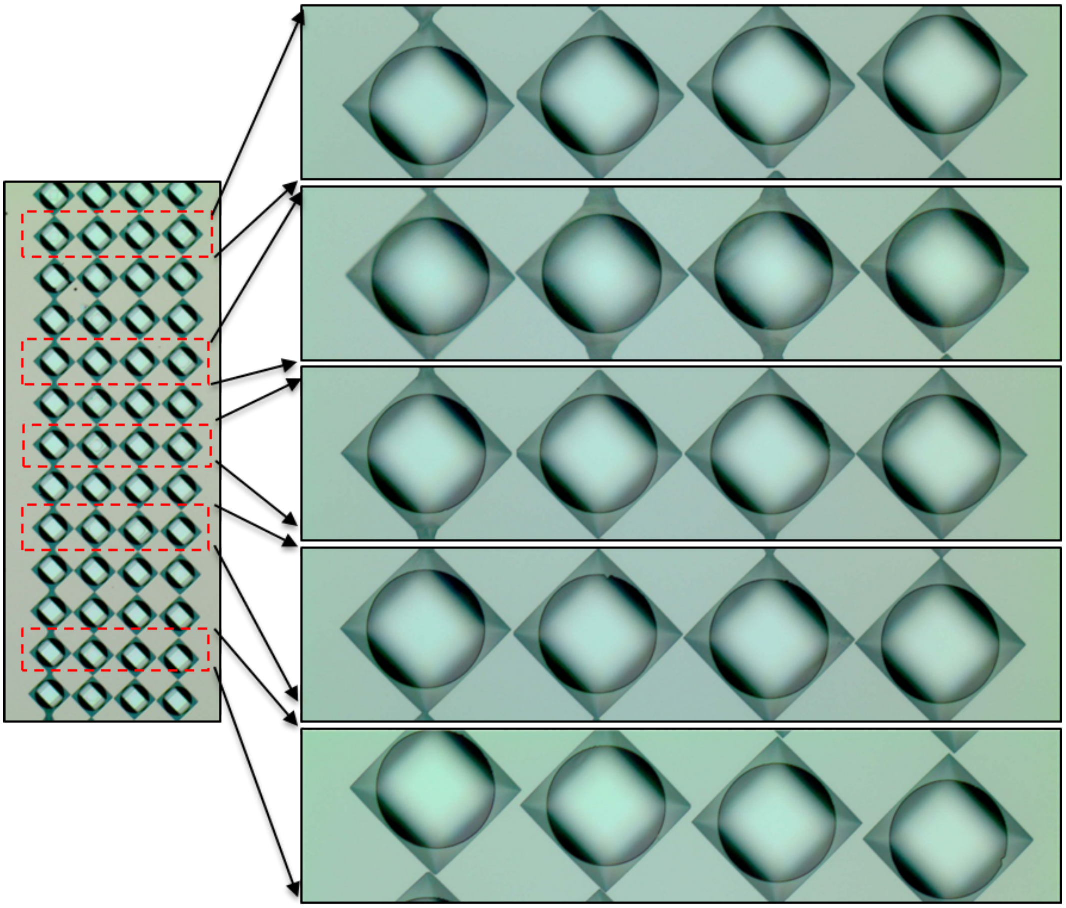

Figure 3. Magnified optical images of the etched profile of the proposed patterns at different places. It can be seen that the self-alignment of the notches takes place at the precise ⟨100⟩ directions (center) while as the direction deviates from ⟨100⟩, the misalignment increases (top and bottom). With a simple visual inspection, the precise ⟨100⟩ directions becomes quite evident without needing measurement of any kind. Only a part of the pattern, near the perfectly aligned direction is shown here.

4. Results and Discussion

Figure 3 shows the optical images of the patterns after etching in 25 wt% TMAH. It can be seen that the notches of the squares formed after etching tends to self-align at a certain location (central pattern in figure 3). The radial diagonals of this particular set of squares constitutes the precise ⟨100⟩ direction. We can also see, that as we move away from this direction on either side, the notches tends to self-misalign itself. Moreover, it can be observed in figure 3 that the misalignment of notches is in opposite direction across ⟨100⟩ direction. Hence the accurate ⟨100⟩ direction can obviously be located using a simple microscope with a simple visual inspection. As stated in previous section, the accuracy of proposed method to identify the ⟨100⟩ direction is determined by etching a 32 mm long rectangular opening aligned along the ⟨100⟩ direction. {011} sidewall oriented at an angle of 45^o to the wafer surface appeared along the edges of the mask

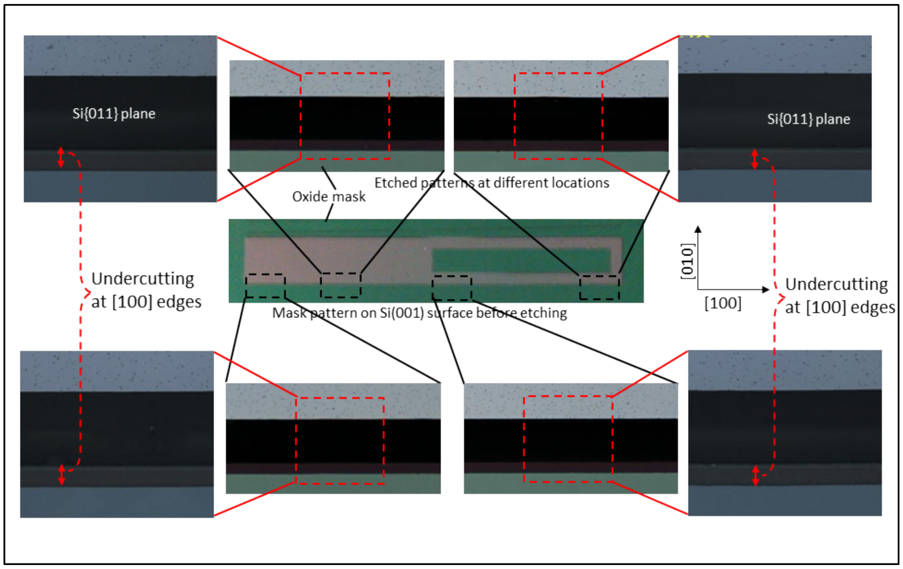

Figure 4. A 32 mm long rectangular opening fabricated by using the set of patterns as shown in figure 3 (center) as the reference ⟨100⟩ directions. The zoomed images show the undercutting at various locations at different magnifications. The undercutting is measured to be varying within sub-micron range.

opening. Undercutting however occurred due to the finite etch rate of {011} planes as shown in figure 4. If the edges of rectangular opening are precisely aligned along ⟨100⟩ direction, the undercutting along the edge should be same. The undercutting is measured at 12 different locations along the length, and the mean of the undercutting lengths is found to be 13.41 μm with a standard deviation of 0.38 μm for etch depth of 61 μm. The maximum variation of the undercutting length implies a misalignment of 6.80×10^{-4} degree, which is negligible. Now, we can state that the proposed method for determining the ⟨100⟩ direction is accurate and can prove to be an effective method for the fabrication of precise 45° micromirrors using wet anisotropic etchants. It may be emphasized here that the main objective of this work is to develop a simple and effective technique which can identify the ⟨100⟩ direction precisely. The study of the characteristics of sidewalls at ⟨100⟩ edge such as smoothness, inclination, reflectivity, etc., is beyond the scope of present study.

5. Conclusions

In short, we have presented a new self-aligning and measurement free pre-etched pattern to determine the ⟨100⟩ direction on Si{001} wafer. The proposed pattern aligns itself in a straight line at the ⟨100⟩ direction while it misaligns itself at other directions. The extent of misalignment is a measure of deviation from the ⟨100⟩ direction. The proposed method does not need any measurement to locate the ⟨100⟩ direction. The accurate ⟨100⟩ direction becomes very obvious due to the alignment of notches and can be easily identified by visual inspection under a simple microscope. The accuracy of the proposed method is demonstrated by fabricating a long opening aligned along the ⟨100⟩ direction based on the proposed method. The sub-micron standard deviation of 12 measurements implies that the method to determine the ⟨100⟩ direction is fairly accurate.

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