Micromachining of $\{111\}$ plates in $\langle 001 \rangle$ oriented silicon

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Abstract. We introduce a new way to micromachine $\langle 111 \rangle$ oriented plates on $\langle 001 \rangle$ silicon wafers by anisotropic wet chemical etching. The process involves double-sided wafer-processing. Precision alignment, however, is only required at one side.

There are basically two ways to etch silicon: dry and wet chemical etching. In micromachining, the control of the shape of the structure is accomplished by anisotropic etching through mask openings. The anisotropy of wet chemical etching is related to the crystal structure of silicon, while that of dry etching stems from the momentum of ions impinging the substrate. The latter gives us much more freedom of design, however, the control of dry etching is much more cumbersome and the equipment much more expensive. Therefore, any new process trick to increase the number of geometries that can be obtained by wet chemical anisotropic etching is of interest.

In this paper, techniques are demonstrated to etch thin $\{111\}$ plates in $\langle 100 \rangle$ silicon. These plates can be used as building blocks in, for example, microfluidic systems for valves and pumps.

All micromaching processes described in this paper are accomplished in 25 wt% KOH at 78 °C.

Figure 1. Cross-section of etch pits resulting from wet chemical anisotropic etching of $\langle 001 \rangle$ silicon. The dashed lines indicate planes, parallel to the walls of the large etch pit. If one is able to etch along these lines, $\langle 111 \rangle$ oriented plates can be fabricated.

Figure 1 shows the typical etch pits which are obtained when etching $\langle 001 \rangle$ silicon. The etch pits are bounded by $\{111\}$ planes.

If a method could be developed to etch along the dashed lines, $\langle 111 \rangle$ oriented plates could be obtained. Figure 2 shows a possible solution [1]. The thickness of the resulting plates is defined by the position of the mask openings with respect to each other, by the $\{111\}$ etch rate, by the exact thickness of the wafer and, of course, by the deviation of the mask alignment from the crystallographic orientation on *both sides* of the wafer. The latter can be reduced to less than 0.05°, by means of a mask pattern described by Vangbo and Bäcklund [2]. The wafer thickness, however, introduces a problem due to the spread of thickness of commercially available wafers. Therefore, we looked for a

Figure 2. Cross-section of a process for micromachining $\langle 111 \rangle$ oriented plates using double-sided precision mask alignment.

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Figure 3. Cross-section of the new process for micromachining $\langle 111 \rangle$ oriented plates using precision mask alignment only at one side.

method to achieve a result similar to that in figure 2, but with the requirement of precision alignment of a mask to the crystallographic orientation only on *one side* of the wafer.

The idea of this new process came up when we considered the micromachining of a wafer thick mass of

rectangular shape, suspended by thin beams in a $\langle 001 \rangle$ silicon wafer [3,4]. At both sides of the wafer, mask openings are aligned such that both etch pits will meet each other in the middle of the wafer, resulting a convex hole. This is shown in figure 3, step 3–4, left hole. The sharp corners of the convex hole will now be blunted because they are attacked in the $\langle 110 \rangle$ direction. If stopped in time, straight $\{110\}$ walls are obtained (step 5, left hole). This is a quite critical process: if one etches too long the etch form will fold into a concave shape. Here we continue the process until $\langle 111 \rangle$ bounded etch pits in the trench have formed [5]. An adjacent mask opening on the frontside of the wafer will result in an etch pit and a $\{111\}$ wall. The width of this wall is given by the mask openings, the underetching, and the alignment precision at *only* the frontside. Note that misalignment of the mask opening on the rear side has no influence on the wall thickness.

Using this process idea we are able to produce structures with high precision and reproducibility. All three dimensions of the $\{111\}$ plates can be defined on the front side mask. In figure 4, different design possibilities are illustrated. The thickness of the $\{111\}$ plates is defined by the distance between the mask openings at the front side of the wafer, see figure 4(a). Plates of different thicknesses can be fabricated in one wafer. The wafer thickness does not influence the plate thickness. The height of the plate can be controlled by the size and position of the mask openings at both sides of the wafer, which is shown in figures 4(b) and (c). The only function of the rear side mask opening is to switch over the $\{111\}$ planes. To be independent of the wafer thickness and the alignment of the rear side mask, the mask opening on the rear side should be chosen to be large enough that the height (h_f), is always defined by the

Figure 4. Cross-sections of possible geometries. (a) The thickness (t_p) of the $\{111\}$ plate is defined by the distance between the mask openings at the front side of the wafer. (b) The effect of changing the size of the mask opening (m) at the front side. (c) The effect of the position of the mask edge at the rear side.

Figure 5. Some SEM pictures of micromachined structures. (a) Thin {111} plate, (b) thin {111} plate after fusion bonding, (c) magnification of {111} plate of (b), (d) 3D structured rosette.

Figure 6. Left: Magnified drawing of the mask underetch. Top right: Measured underetch as function of time on both sides of the mask. Bottom right: Drawing of the observed profile.

front side mask, see figure 4(b), geometries I and II and figure 4(c), geometry V.

In figure 5 we show some examples of micromachined $\{111\}$ plate structures. Besides the relatively simple structures, more complicated spatial oriented structures have been fabricated by positioning the $\{111\}$ plates in perpendicular directions and switching over the $\{111\}$ planes in a controlled way. Figure 5(d) shows an example: a 3D-structured rosette. Notice that none of the machined structures are sensitive to overetching, because all are bounded by $\{111\}$ planes and are formed without the need of compensation structures.

Etch experiments have yielded interesting results. The processes shown in the figures 2–4 all result in $\langle 111 \rangle$ oriented plates. There are two angles the plate faces make with the wafer surface, approximately 54.7° , which is the normal inclination of the $\{111\}$ walls in etch pits, and the other one makes the complementary angle, viz. 125.3° . In our observation, the mask is undercut differently on either side of the plate. As can be seen in figure 6, the underetching is larger at the large inclination angle side. Measuring the underetch as function of etch time reveals that before the wall on the left side of the etch pit is exactly vertical (at $t = t_2$) the underetch is the same at both sides, see figure 6, top right. However, during further etching, the underetch rate is about 2.5 times larger at the side of the large inclination angle than at the opposite side. The plate thickness is also not constant, but shows a tapered profile, see figure 5(b). Closer inspection reveals a profile such as is drawn in figure 6, bottom right, with measured angles of $54.5^\circ \pm 0.5^\circ$ and $124.0^\circ \pm 0.5^\circ$. We also observed that the $\langle 110 \rangle$ oriented planes, as indicated in the figure 3 (step 4–6) were not flat, but had a ‘zigzag’ structure. More research on these observations is currently performed in our group (by A J Nijdam *et al*) and will be published elsewhere [6].

Conclusions

The presented method allows the fabrication of thin $\langle 111 \rangle$ oriented plates. It offers promising opportunities for etching new geometries, applicable in, e.g., check valves, pumps and injection nozzles. These applications are currently under investigation and will be described in forthcoming papers [7].

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