3.4 Etching

Once layers have been deposited and a photolithographic process has been done, the most common step is a selective removal of the layer from the unmasked areas of the wafer with the so-called etching processes. This depends on the previous steps that have suffered the materials on the wafer (since their properties could have been significantly affected) and the deposition mechanism which has been used for obtaining the layers (a plasma-deposited silicon oxide is etched much faster as compared to its counterpart thermally growth).

Within etching processes, two groups can be distinguished: the wet etching, by active components dissolved in aqueous or organic solutions and the dry etching, that uses ionized gases as reactive agents (plasma).

3.4.1 Wet Etching

By wet etching it is understood the elimination of a material by its dissolution in an adequate etching solution. It is mainly used for cleaning, shaping and polishing.

To etch different materials a large variety of chemical agents can be used. It should be taken into consideration, however, that solutions used in etching processes must etch exclusively the desired film, without affecting underlying layers or lithographic masks. Thus, etching solutions must be highly selective, defining the selectivity as the ratio between the etching rates of two different films in the same etching solution.

Generally, wet etching provides a higher degree of selectivity at a higher rate as compared to dry etching. Modification of wet etchant and/or temperature can also alter its selectivity. Etching mechanism consists on reactant transport to the surface, surface reaction and by-products transport away from the surface, exactly in the same way as it does the growing mechanism described in section 3.2.2.1, having the diffusion or the surface kinetics limitations. If the reaction is surface kinetics limited, etching strongly depends on the temperature. Moreover, it appears new factors inherently associated to wet etching. As an example could be the presence of gaseous bubbles that break the boundary layer or the etching rate enhancement by solution agitation.

Two different etching types can be defined. **Isotropic:** When the etching rate is equal in all directions. **Anisotropic:** When there exists a preferential etching direction. Fig. 3.7 shows schematically the profiles that are obtained with both etching mechanisms. The etching of polycrystalline and amorphous materials tends to be isotropic. single-crystalline materials may undergo isotropic or anisotropic etching depending on the etching solution used.

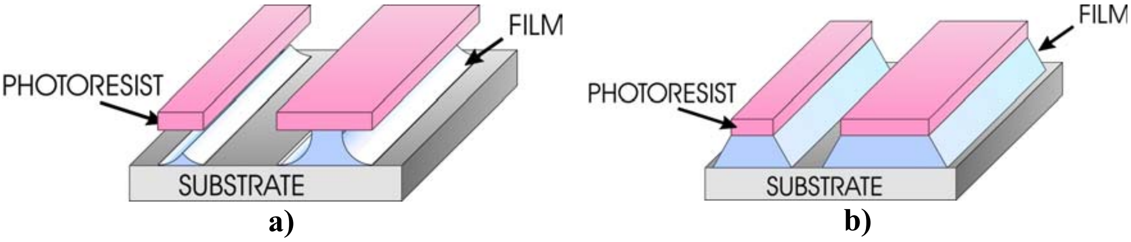

Fig. 3.7. Different etching profiles obtained. a) Isotropic, b) Anisotropic.

The etching factor is defined as the relationship between the etching depth and the lateral etching (underetching), measured under the protection mask. Obviously, this factor will be the unity for isotropic etching and greater that one for anisotropic processes. Since the mask transfer has to be transferred as accurate as possible, the etching factor of the dissolution used is extremely important.

The most used techniques in wet etching are those of dip and spray. The election of any of these depends on the etching process requirements.

The dip technique consist of submerging the wafer into the etching solution. Often agitation is needed in order to increase the uniformity of the etching and to improve the reproducibility, enhancing the elimination of by-products, removing them from the surface. It permits high degree of process control and guarantees high-quality etching.

The spray technique offers an improvement in the etching quality due to a reduction in the lateral etching by directing the etching solution orthogonal to the surface, thus, etching factors higher than the unity are obtained. Moreover, the spray equipment supplies continuously the surface to etch with fresh reagents, resulting in a constant etching rate, since the reaction products are not maintained near the surface.

3.4.1.1 Anisotropic Etching on Silicon

Crystalline silicon forms a covalently bonded structure that coordinates itself tetrahedrally, making up the diamond-cubic structure shown in fig. 3.8, that can be represented as two interpenetrating face centered cubic (fcc) lattices, one displaced (1/4,1/4,1/4) respect to the other. The final unit cell consists on a fcc lattice, but with two atoms per unit cell.

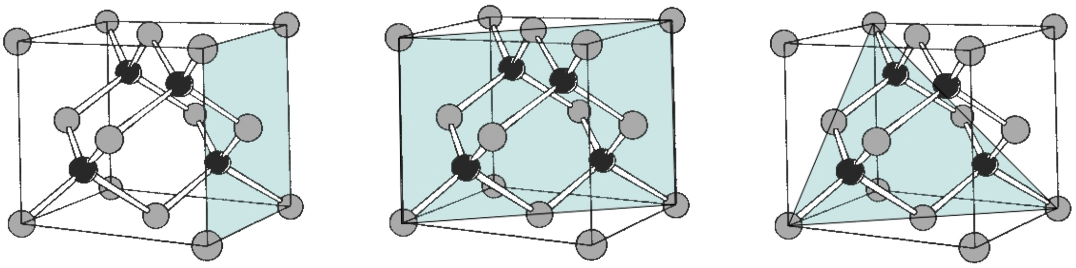
a) **b)** **c)**

Fig. 3.8. Crystalline silicon tetrahedral structure and different crystallographic planes: a) plane (100), b) plane (110), c) plane (111).

In order to appreciate the different three-dimensional shapes resulting from etching a single crystal of silicon (SCS) and to better understand the next subsection, related to corner compensation, some of the more important geometric relationships between the different planes within the Si lattice need to be known.

The etching of a material proceeds by successive dissolution of the material surface. If it is surface-reaction controlled, for SCS the etch rate will depend on the crystallographic orientation at the surface. Thus, the process will be much slower on the (111) planes (with a 7M KOH etching at 80ºC, measurements provided an etching ratio of 2.55 nm/min, which is negligible as compared to the 1.4µm/min for the (100) plane) since atomic packaging is denser in this case. Etching rate progressively increases if planes (110) or (100) are considered. On the contrary, if the process is diffusion limited, the etch rates are very high and tends to be uniform in all direction, being the process isotropic.

For our following analysis, we will only consider silicon wafers with (100) as surface planes. Due to the very high difference between the (100) and (111) etching rates, we will consider the (111) as non-etching planes. Hence, any geometrical pattern defined on the SCS surface will ultimately be bounded to the closest (111) planes.

As an example, in fig. 3.9 it can be seen the effects of anisotropic etching, obtaining truncated V-grooves that deepen but do not widen as the etching time increases. If this time is long enough, the (111) planes intersect and the (100) bottom plane disappears, creating a V-groove. It can be proved **[8]** that the final width W_{etch} can be defined as

$$W_{etch} = W_{mask} - \frac{2z_{etch}}{tan(54.74^{o})} \tag{3.6}$$

where W_{mask} is the mask opening and z_{etch} is the etched depth.

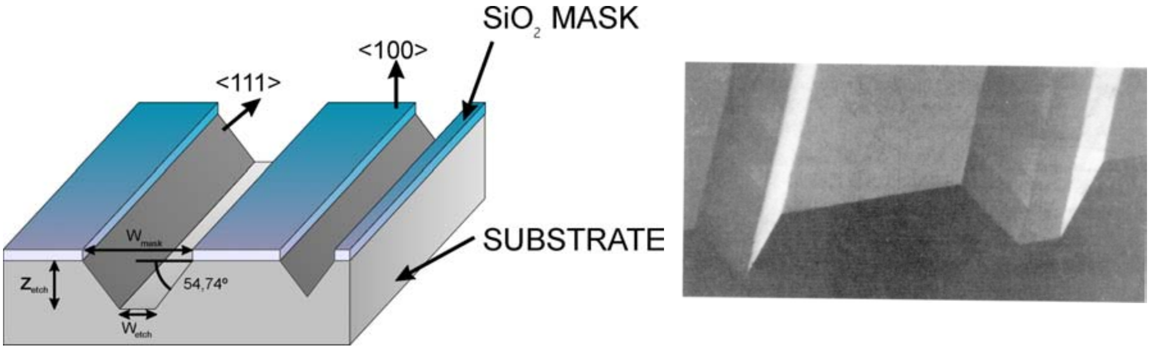

Fig. 3.9. Silicon anisotropic etching of a rectangular mask pattern, forming V-Grooves following the (111) lattice planes.

The etch stop at the <111> sidewalls' intersection occurs when the depth is about 0.7 times the mask opening.

When etching convex corners, deformation of the vertex occurs due to simultaneous etching in different directions. This effect is known as undercutting, and causes a significant reduction on the size of the required pattern. That is specially worrying in the fabrication of accelerometers, where its specifications will be defined considering 90º convex corners. Results from this undercutting in an accelerometer can be seen in fig. 3.10.

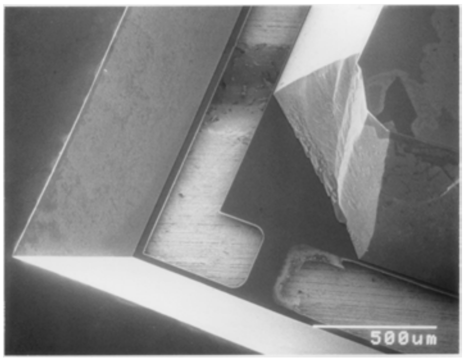

Fig. 3.10. Mass reduction in the seismic mass of an accelerometer due to undercutting.

Undercutting of convex structures in KOH has been observed to depend exclusively of the (411) planes **[12]**. As shown in fig 3.11, these planes, on the convex under-etching corner, are not completely laid free. Thus, only fractions of the main planes can be detected, being overlapped by the (411) planes, causing rough surfaces to appear.

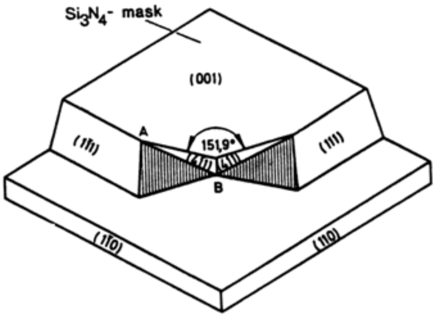

Fig. 3.11: Planes involved in convex corners during KOH etching, after **[8]**.

These undesirable effects can be reduced or even prevented with the so-called corner compensation structures, which are added to the convex corners in the mask layout. Depending on the etching solution, different compensation patterns are used. Some of them are presented in figure 3.12 for silicon etching in KOH.

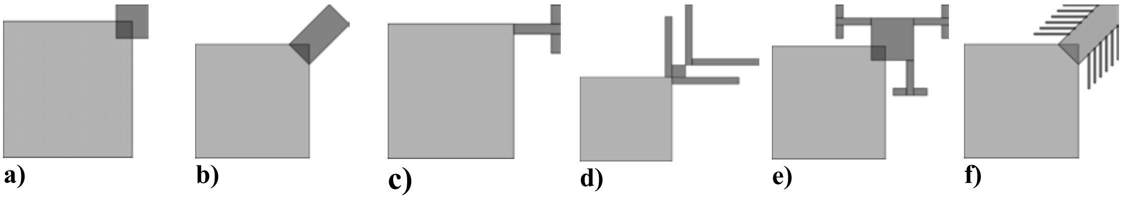
a) **b)** **c)** **d)** **e)** **f)**

Fig. 3.12. Compensation structures (dark gray) on convex corners so as to avoid undercutting **[13]**.

All the patterns from the previous figure minimize the undercutting effect. The increase in its complexity is due to the avoiding of rugged surfaces. Basically, all are designed under the principle that etching on the convex corner has to be delayed as much as possible, trying to keep the basic structure of the convex corner. Thus, considering the different etching rates of the (100) and (110) planes, several patterns can be obtained. As a rule, the length of the compensated beam is calculated primarily from the required etch depth (z_{etch}) and the etch rate ratio $R_{etch}(411)/\ R_{etch}(100)$, with the expression

$$L_{comp} = 2z_{etch}\frac{R_{etch}(411)}{R_{etch}(100)} - \frac{B_{(110)}}{2tan(30.9^{o})} \tag{3.7}$$

where $B_{(110)}$ is the width of the (110)-oriented beam. Theoretically, $R_{etch}(411)/\ R_{etch}(100)$ has been reported to vary from 1.6 when a 15% KOH etching solution is used to 1.3 at above 40% of KOH, where the value flattens and that etch does not depend on the temperature on the 60ºC to 100ºC range **[8]**. However, experimental results done at CNM **[14]** with 40% KOH at 75ºC have reported a $R_{etch}(411)/\ R_{etch}(100)=1.45$. Since this will be the etching solution used on our device fabrication, this value will be considered as correct. For evaluating the necessary compensation patterns, a simple calculation could be done: etching a 450µm thick wafer would require a 1300µm long pattern in every convex corner. Since these figures do not play any role on the final device, it is essential that by the end of the etch all the compensating structure should have disappeared. It also has been studied **[15]** that pyramid formation is prevented if compensation corner patterns, similar to those shown in Fig. 3.28c, are asymmetric, that is, with both branches of different length.

Although it is an extremely employed and useful micromechanical technique, corner compensation requires significant amount of space, and often the method can be only applied to simple geometries.

3.4.1.2 Isotropic Etching

Amorphous materials, such as silicon oxide or silicon nitride are isotropically etched on wet etching. The degree of lateral etching that occurs under the mask is of the same order of magnitude than its depth. Moreover, as the etch time increases, both the underetching and the etch deep enlarges (fig. 3.13). Thus, the resulting etched patterns show more symmetry and rounding. They can be even perfectly rounded if agitation accompanies the etching, since then the process is diffusion limited.

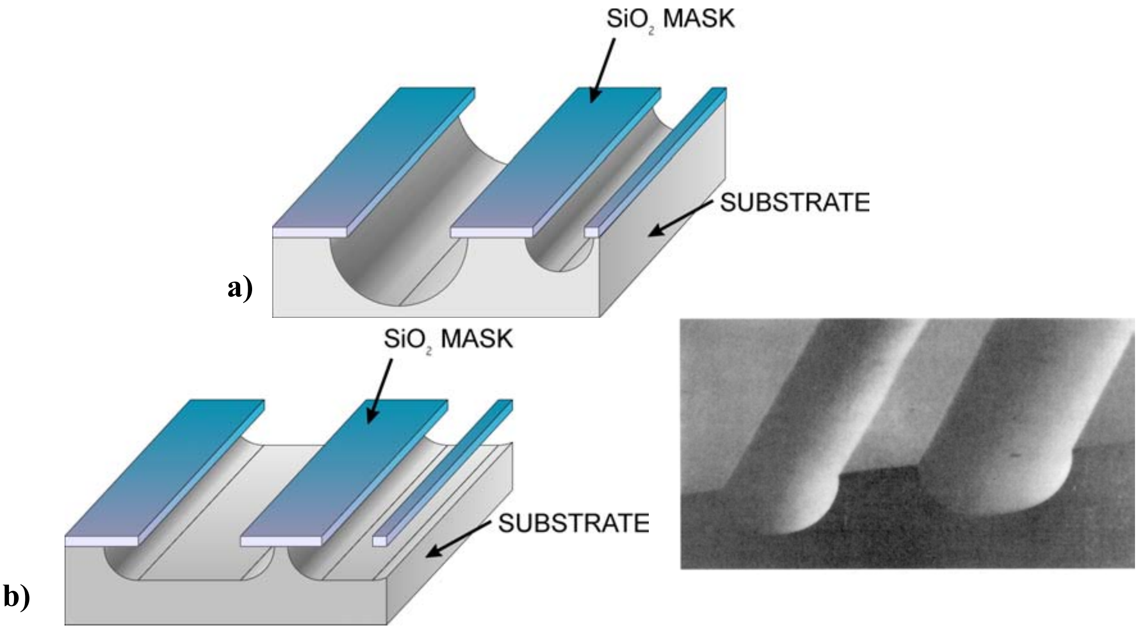

Fig. 3.13. Isotropic etching of Si with (a) and without (b) etchant solution agitation **[16]**.

It can be noted that isotropic etching causes a dimension reduction due to lateral underetching. Thence, device with dimensions below 2µm cannot be obtained by this method and requires another technique that allows anisotropic etching of amorphous layers.

3.4.2 Dry Etching

By dry etching it is understood a family of methods by which a solid state surface is etched through an ionized gas phase, physically by ion bombardment, chemically by a chemical reaction with reactive species at the surface, or combined physical and chemical mechanisms. The plasma dry etching techniques are categorized according to the specific set-up as either glow discharges or ion-beam techniques. On the formers, plasma is generated in the same vacuum chamber where the wafers are