Course material

Course:

Micro and Nanofabrication (MEMS)

Video:

6.5 Wet etching 5

Concepts (extracted from automatically generated subtitles):

Etch rate drops. Very thin silicon membrane. Electrochemical etch stop. Passivation potential. Silicon etching rate. Potential of this technique. Bulk parts of a wafer. Vertical direction. End result of the etching. Rectangular opening. Introductory lesson. Etched structure. Bulk micromachining. Boron-doped membrane. Current-voltage characteristic.

to video sequence search
(within Micro and Nanofabrication (MEMS).)

to video

...

notes

summary

0m 0s

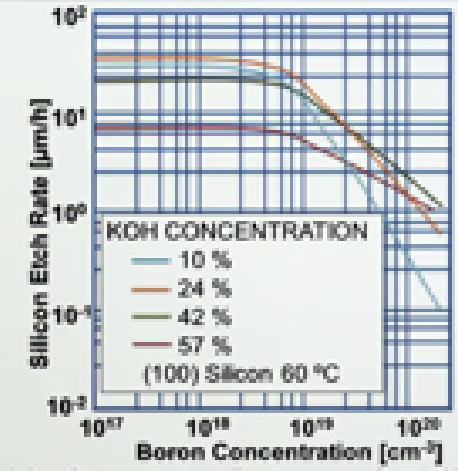
In this lesson we will explain two techniques for stopping the etching

notes

summary

0m 1s

Etch stop by B implantation



(after Seidel et al., J. Electrochem. Soc. 137, 3626 (1990))

- For KOH-based solutions, significant reduction in etch rate for B concentrations in Si above 10^{19} cm^{-3}
- At high B concentration, the Si Fermi level drops and the electrons tunnel into the valence band, where they recombine with holes, rather than staying at the Si surface for regeneration of new OH^- ions
- Hence the etching stops
- Other anisotropic etching baths show similar effect upon B implantation in Si
- This property is used for making thin membranes

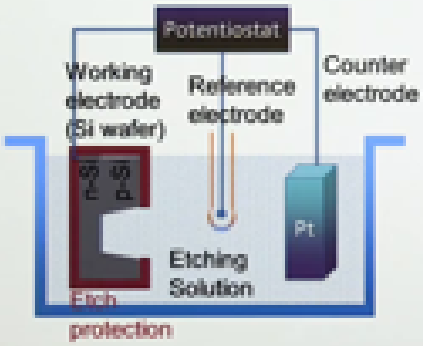
in a very controlled way, allowing the microfabrication of very thin membranes. Then we will illustrate the potential of this technique for bulk micromachining, which is microfabrication by etching through bulk parts of a wafer. In our introductory lesson on wet etching we already mentioned that one can make a very thin silicon membrane by implanting it with boron. And if one etches, then, in KOH solution, the etching stops when one reaches this boron-doped membrane. We can now understand this. The figure shows the silicon etching rate as a function of the boron concentration for different KOH concentrations in the etching bath. For boron concentrations above 10^19 atoms/cm^3, the etch rate drops, and note that this is a logarithmic scale. This is due to the following mechanism: at high boron concentration, the silicon Fermi level drops and the electrons that originate from the negative hydroxyl ions tunnel directly into the valence band rather than staying on the silicon surface

notes

summary

0m 5s

Electrochemical etch stop



(after Wong et al., J. Microelectromech. Syst. 1, 187 (1992))

- Applying a positive potential to the wafer produces holes h^+ at the Si/solution interface
- Two mechanisms involved
  - SiO_2 formation: Si-OH and Si-OH form passivating SiO_2 at surface, splitting off H_2O
  - SiO_2 dissolution by $SiO_2(OH)_x$ complex formation.
- At V below the passivation potential: oxide is formed and etched away
- Above the passivation potential: complete passivation and all etching stops
- The passivation potential depends on dopant type

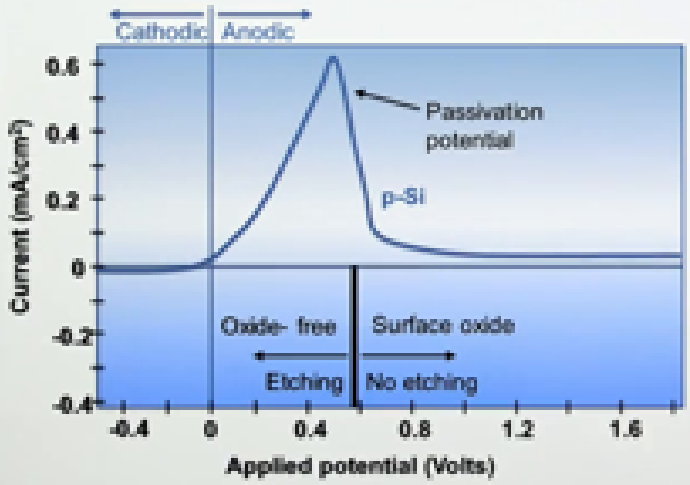
for regeneration of new hydroxyl ions from the water. Therefore the etching simply stops as these hydroxyl ions cannot be regenerated. A disadvantage of the boron etch stop is that we have to use very high boron concentrations. And these are not compatible with standard microelectronic devices, and also these compromise the crystal quality of the silicon. Therefore an interesting alternative for making a thin membrane, is the so-called *electrochemical etch stop.* In this case, we take a lightly p-doped silicon substrate and one deposits on top of that, a lightly doped silicon layer with n-type impurities. Then one brings this substrate in the etching solution, in the KOH solution. So the red part is protection against etching and this part of the wafer is seeing (is in contact with) the etching solution. The end result of the etching is shown here. We have etched through the p-doped silicon, and we recognize the (111) planes here. But when we have reached the n-type doped silicon, the etching stops, and in this way we can make here a thin membrane. How does this work? Two mechanisms are involved. First, we apply a positive potential here, which produces holes at the silicon solution interface,

notes

summary

1m 37s

Electrochemical etch stop



(after Collins, J. Electrochem. Soc. 144, 2242 (1997))

- Current-voltage characteristic of p-doped Si

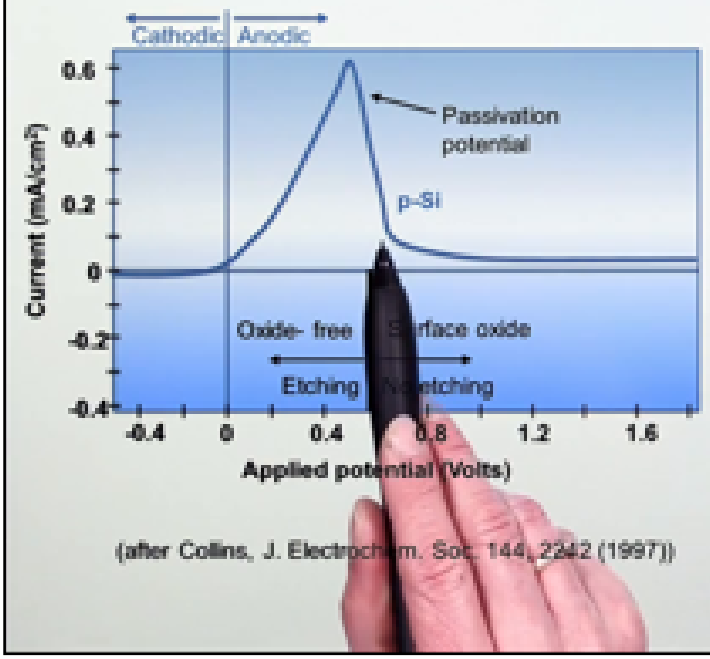
and these attract hydroxyl ions and form silicon dioxide. A competitive process is the dissolution of this silicon dioxide forming this complex ($SiO_2(OH)_x$) that goes into the solution. If the voltage that is applied to the wafer is below the so-called *passivation potential,* the oxide will be formed and will be dissolved, will go into the solution. So there is continuous oxidation, continuous removal of silicon, so that means etching. Above this passivation potential there will be complete passivation by oxidation and all etching stops. Why does it stop at the interface with the n-type doping? That is because this passivation potential changes and depends on the doping type.

notes

summary

3m 25s

Electrochemical etch stop



(after Collins, J. Electrochem. Soc. 144, 2242 (1997))

- Current-voltage characteristic of p-doped Si

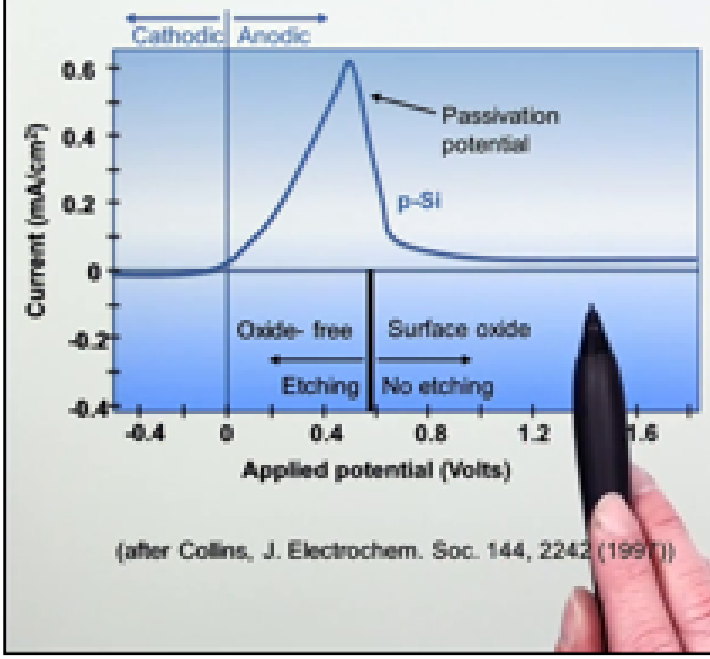
This shows a typical current-voltage characteristic for p-doped silicon.

notes

summary

4m 31s

Electrochemical etch stop



(after Collins, J. Electrochem. Soc. 144, 2242 (1997))

- Current-voltage characteristic of p-doped Si

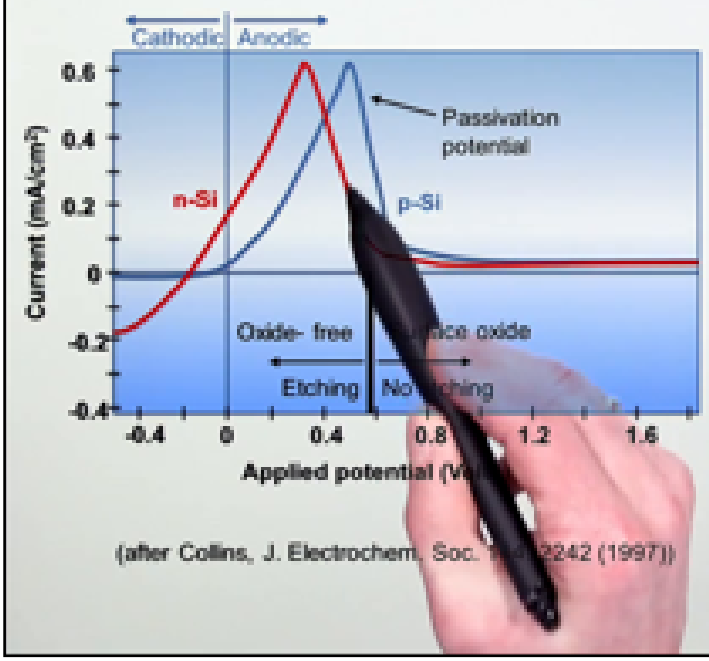
Below the passivation potential, that is on this side, there is a current flowing. As holes get transported to the substrate, where they oxidize the silicon, after which the oxide is removed by formation of the complex, which is an etching process. Above the passivation potential, the current drops

notes

summary

4m 38s

Electrochemical etch stop



- Current-voltage characteristic of p-doped Si
- Current-voltage characteristic of n-doped Si

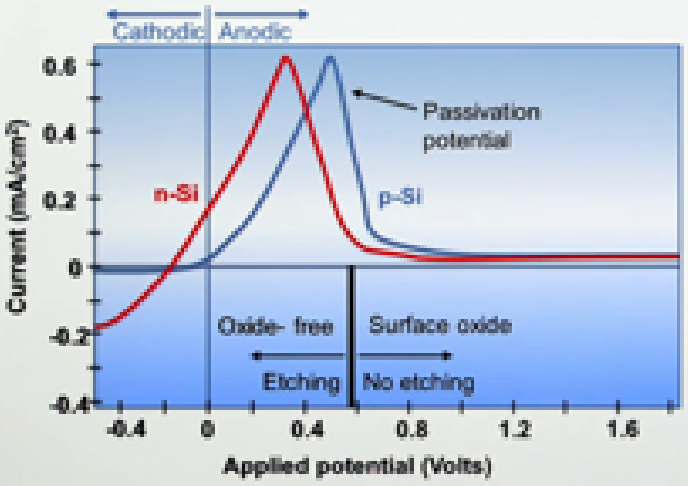
as the surface is covered with an oxide and no etching occurs. Here we have added the current-voltage characteristic of n-doped silicon.

notes

summary

5m 0s

Electrochemical etch stop



(after Collins, J. Electrochem. Soc. 144, 2242 (1997))

- Current-voltage characteristic of p-doped Si
- Current-voltage characteristic of n-doped Si

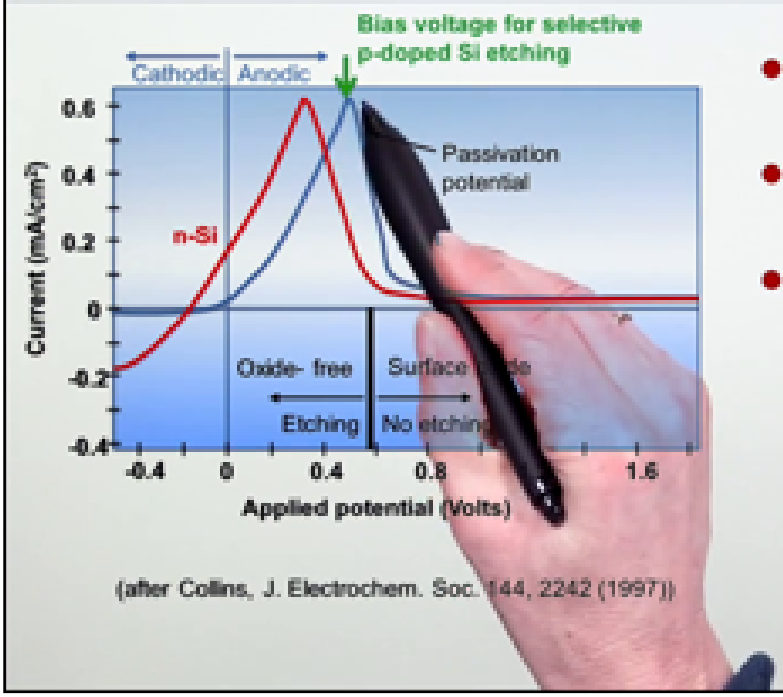
It has a similar behavior but the passivation potential is different.

notes

summary

5m 13s

Electrochemical etch stop



- Current-voltage characteristic of p-doped Si
- Current-voltage characteristic of n-doped Si
- By selecting the bias voltage at high p-Si etch rate and zero(low) n-Si etch rate, one can **selectively remove the p-Si**

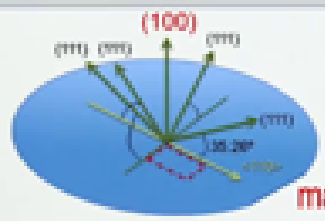
So this shows where we have to put the bias voltage. It's where there is the green arrow.

notes

summary

5m 20s

Bulk micromachining

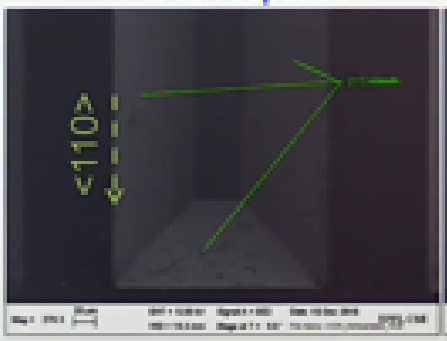


mask opening

KOH etching of a (100) wafer with rectangular mask oriented along the in-plane <110> direction

K salt deposition

After neutralisation with HCl



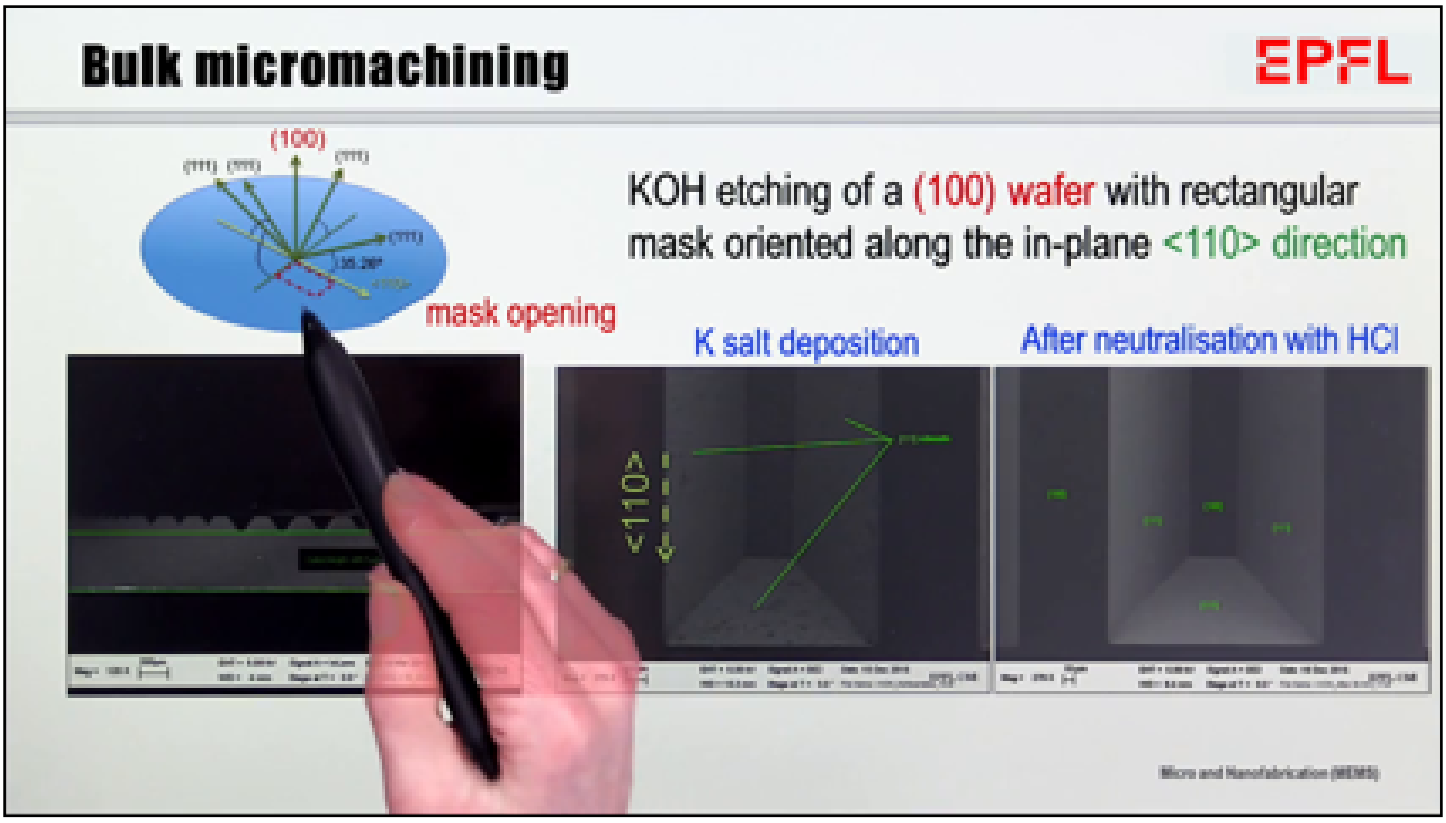
Micro and Nanofabrication (MEMS)

When this is the voltage we apply, we will have high etching of p-doped silicon, and zero or very little etching of n-doped silicon. And then when reaching the membrane with n-type doping, the etching will stop.

notes

summary

5m 27s

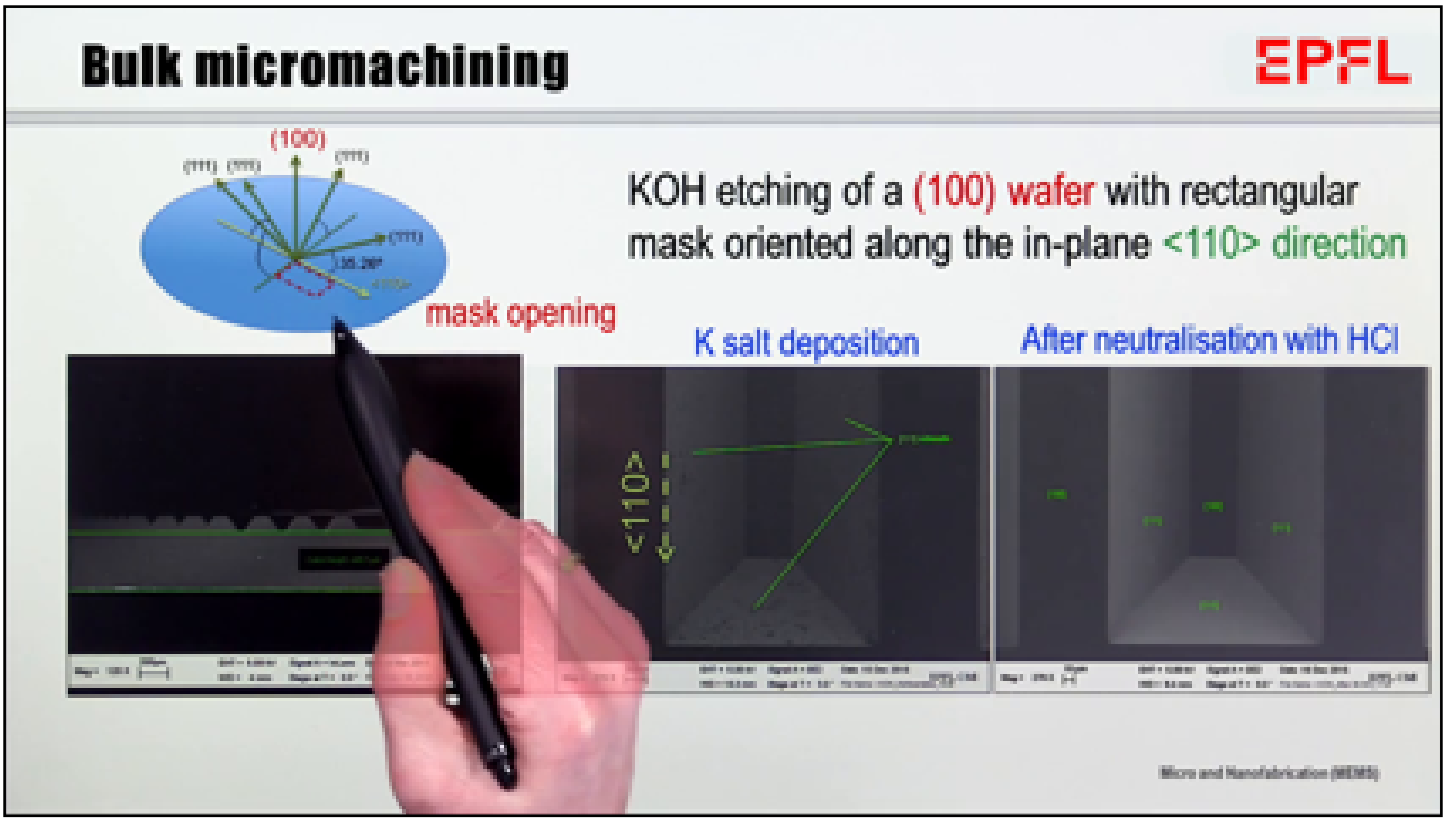


We now give examples of bulk micromachining of a (100) oriented silicon wafer in a KOH bath. We draw the wafer with the four vectors

notes

summary

5m 49s

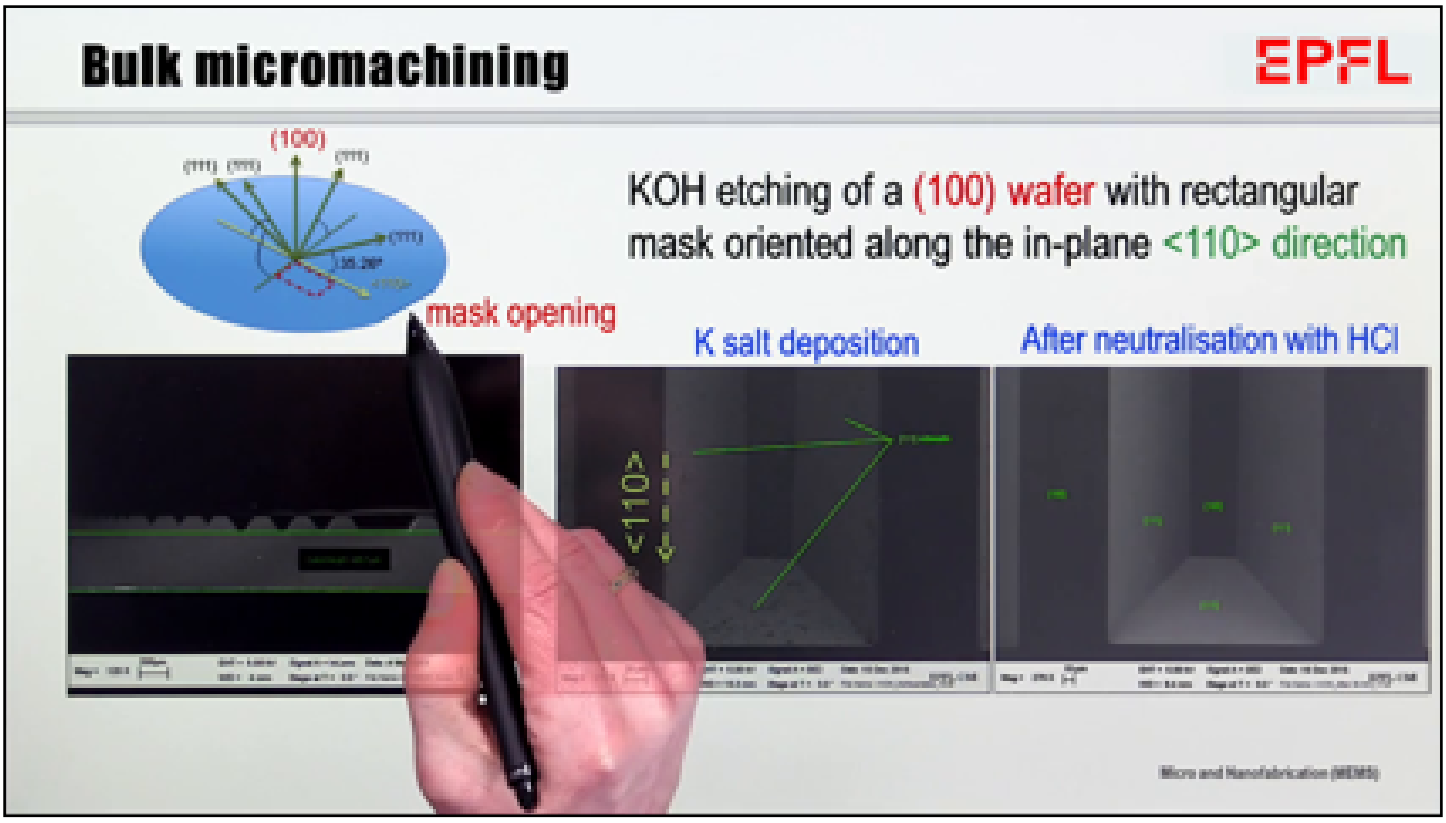


indicating the norms to the respective (111) planes. We have covered the wafer with a mask with a rectangular opening,

notes

summary

6m 1s

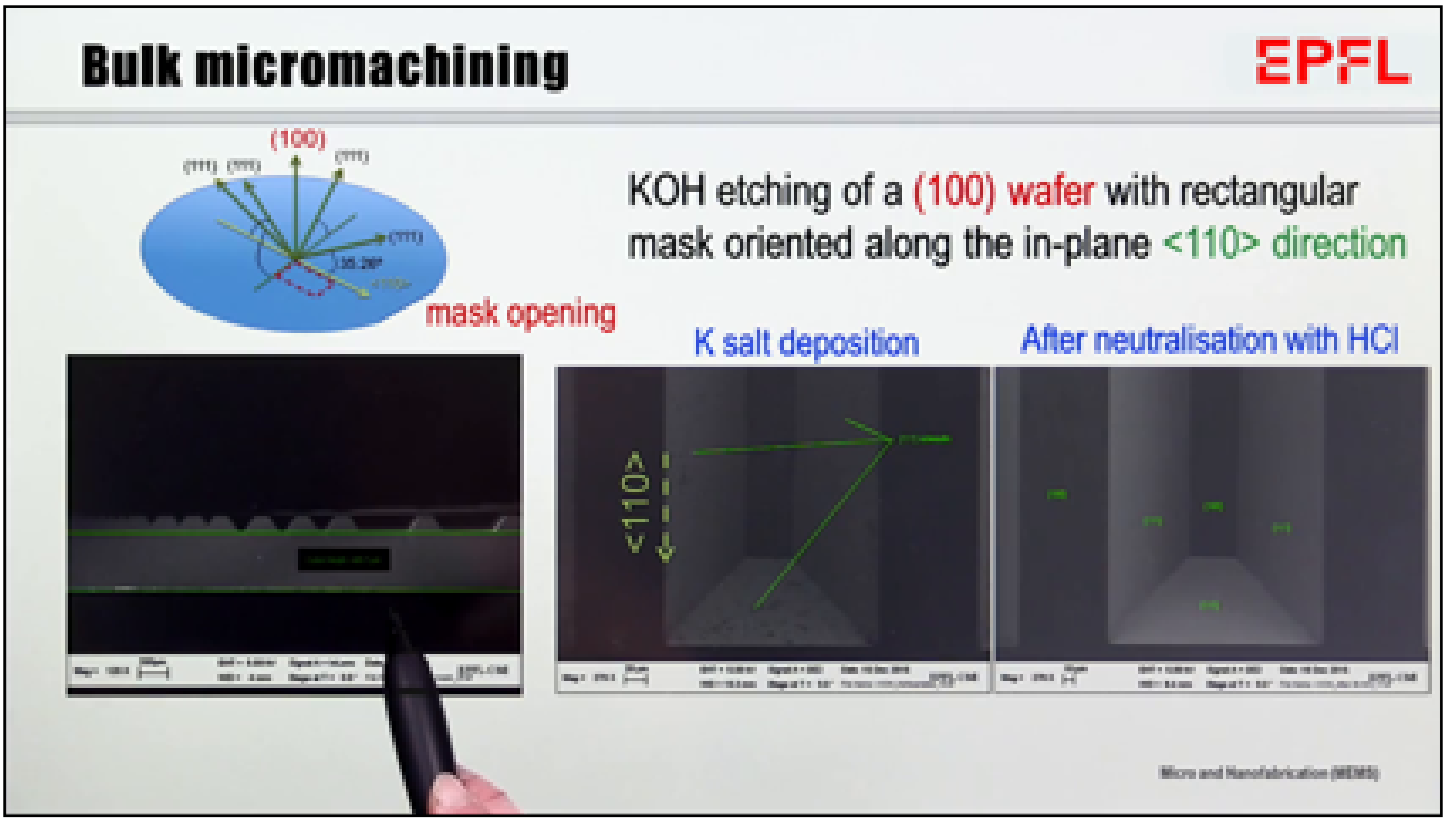


which is oriented along the <110> direction in real space.

notes

summary

6m 12s



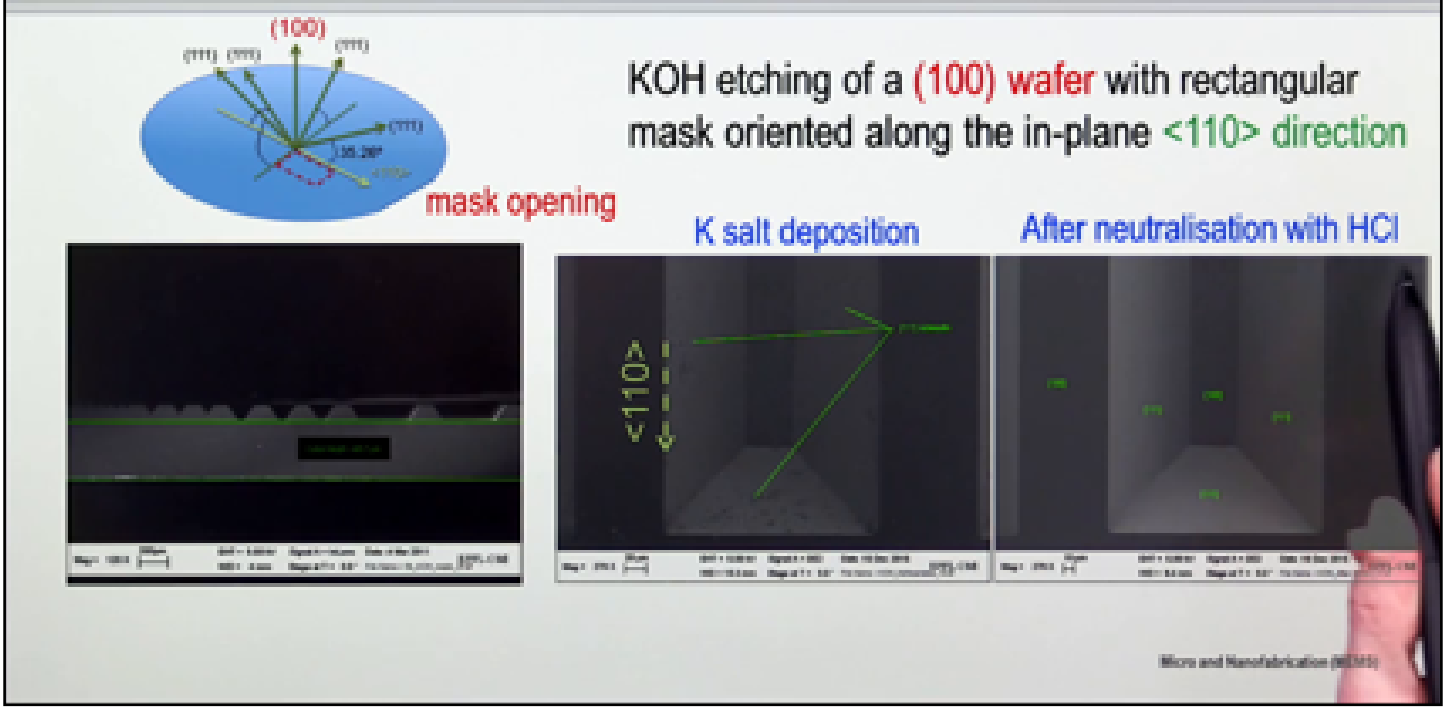
The picture below shows a cross section of the etching, where one recognizes the typical V-shape for a rectangular opening.

notes

summary

6m 16s

Bulk micromachining



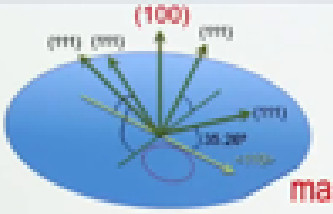
If the <110> direction is in this direction, the (111) planes, indeed, are oriented with these facets. After etching, potassium salt residues originating from the KOH bath, may remain on the etched structure. These deposits can be removed by immersing the wafer in an HCl bath.

notes

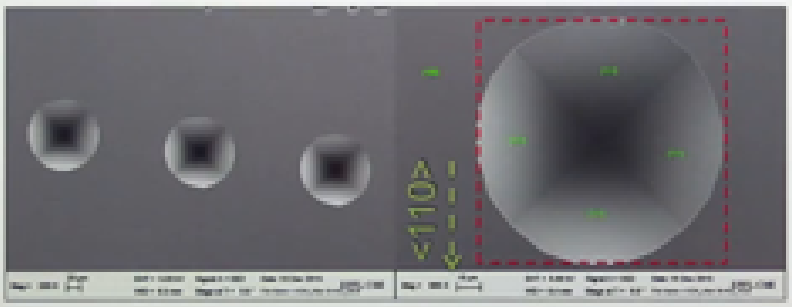
summary

6m 30s

Bulk micromachining



KOH etching of (100) wafers with arbitrary mask → underetching of the mask and formation of inverted pyramids or 'roofs'



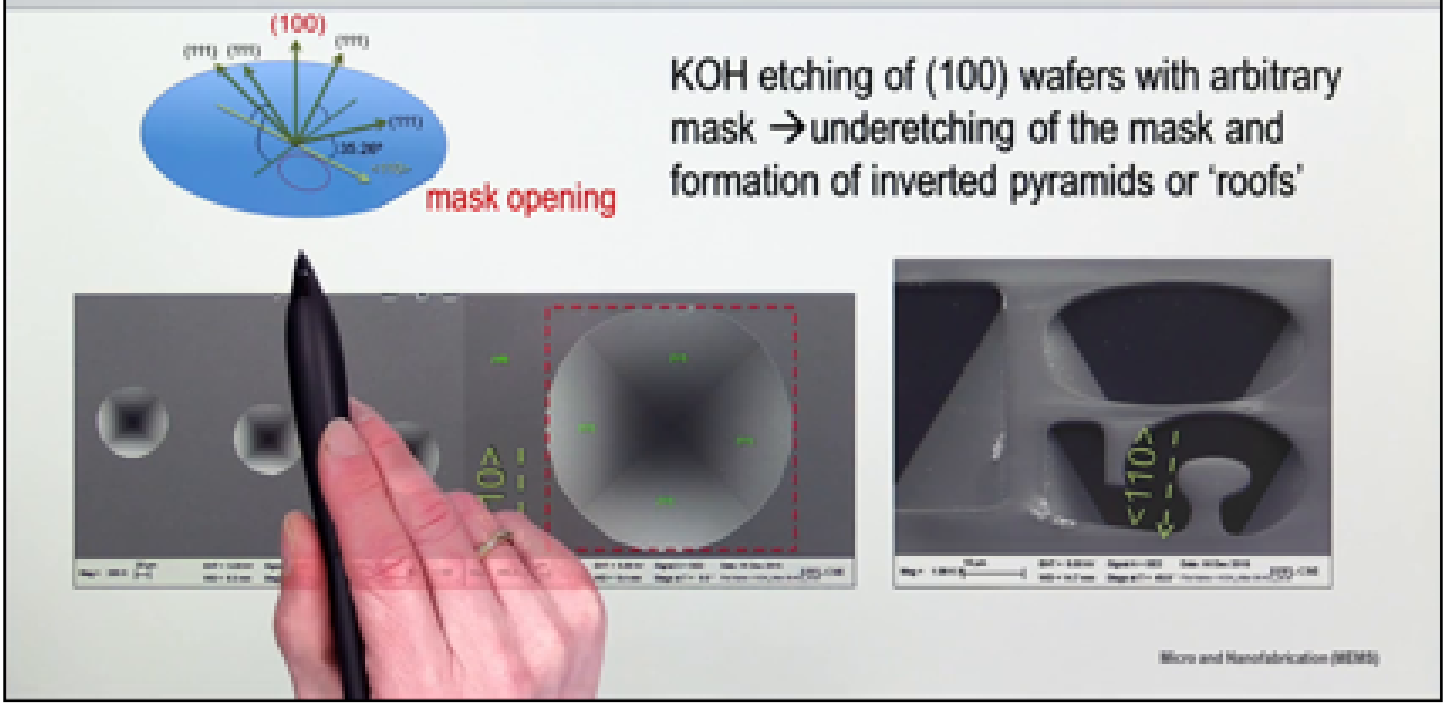
We have again drawn the same (100) wafer

notes

summary

7m 1s

Bulk micromachining



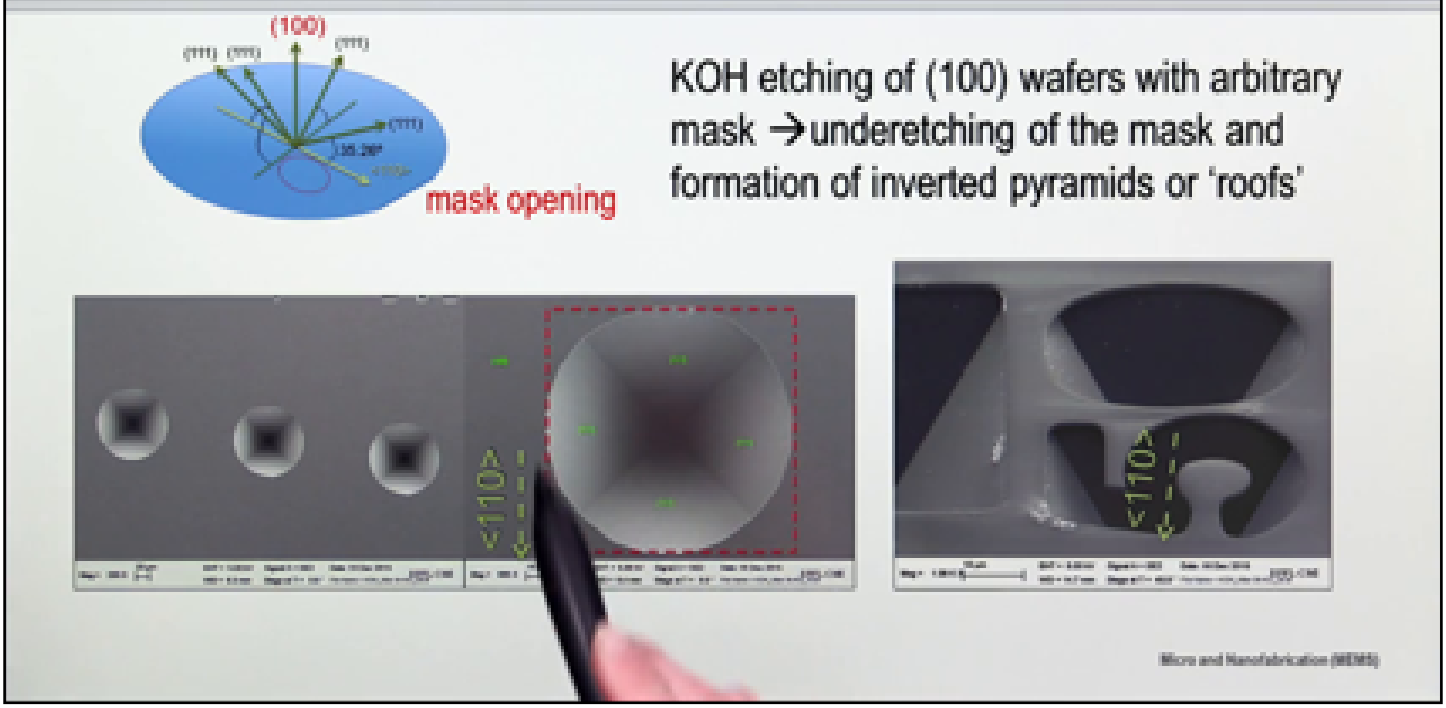
but now we have deposited a mask with a circular opening, like given by this dashed line.

notes

summary

7m 4s

Bulk micromachining

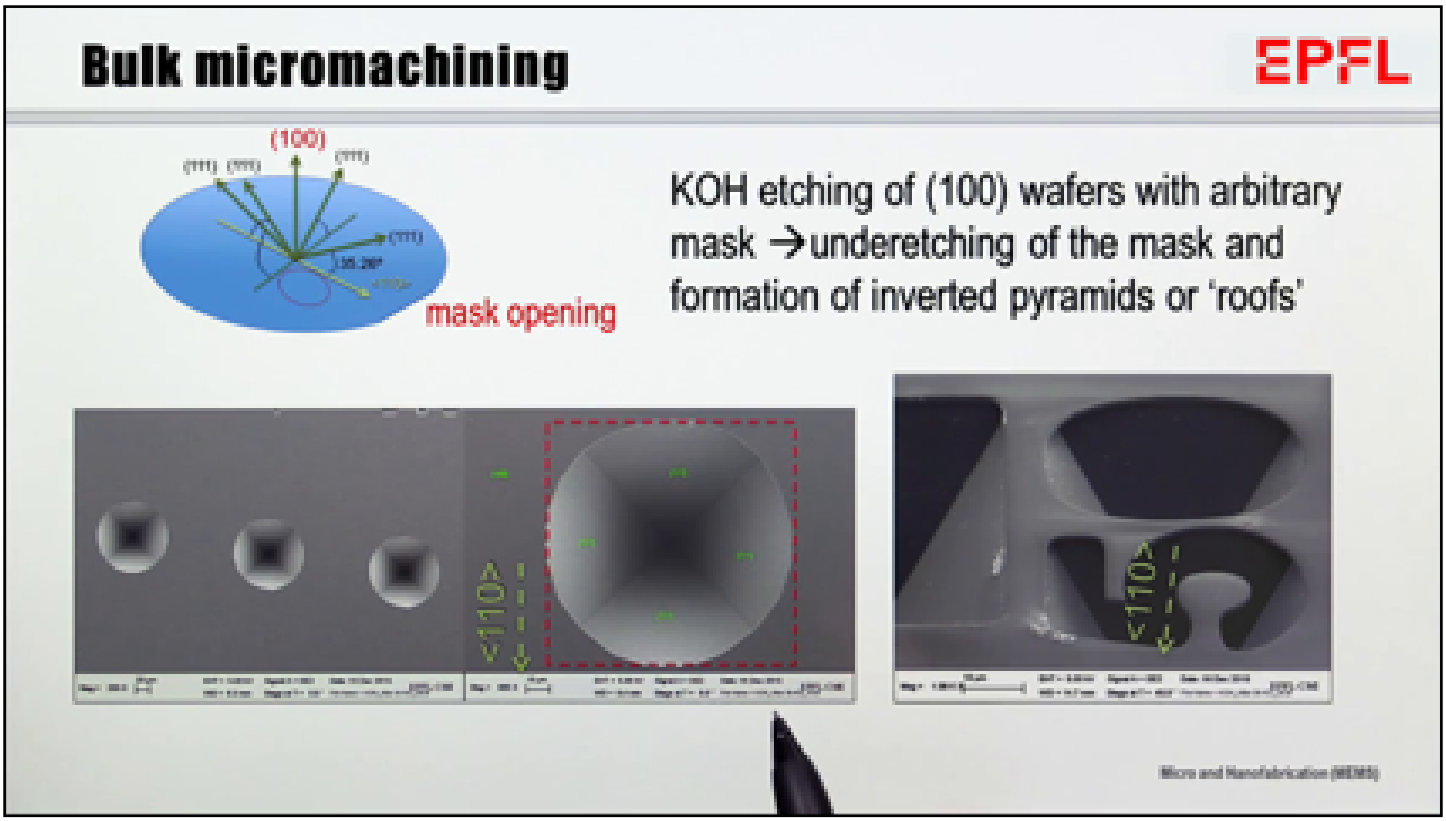


If we look through a circular opening after etching, we see, again, four (111) planes. And we see that the mask is underetched, so a complete inverted pyramid is present underneath the circular mask. The contour of the basis of this pyramid is shown by this dashed line. The end result of such a microfabrication step is a square or more generally a rectangular structure,

notes

summary

7m 17s

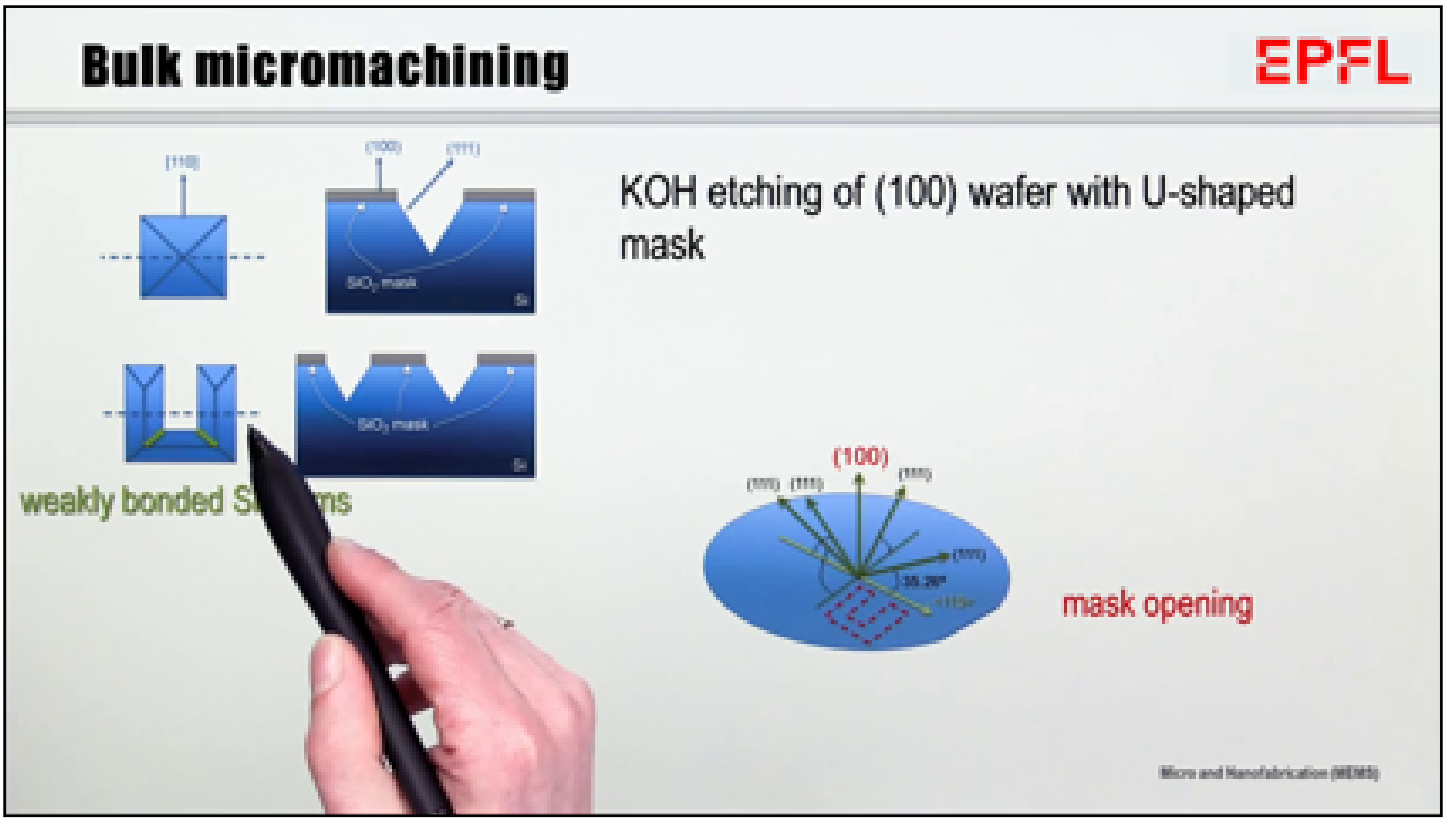


which encompasses all extremities of the mask. That is because for this situation,

notes

summary

7m 56s



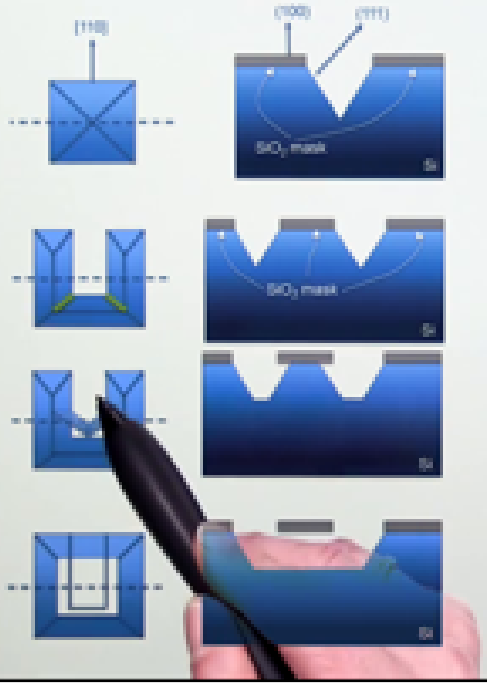
all (111) planes are perfectly protected by the mask and no chemical attack via etching of other crystal planes are possible to remove the silicon atoms on a (111) plane. The picture here shows, again, an arbitrary mask and underneath, one sees indeed again, these V-shaped underetched structures. This example shows the etching of a (100) wafer where we have here a U-shaped mask. We know already that the final structure that will be etched will be an inverted pyramid, the basis of which encompasses all extremities of the mask opening. So the pyramid will be like that. However, before reaching this end result, the etching bath will etch rectangular openings, like shown here, and at this stage the etched structure is stable, and has (111) planes

notes

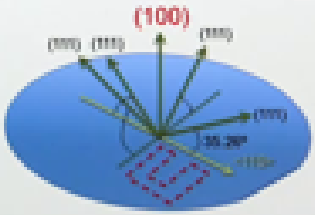
summary

8m 7s

Bulk micromachining



KOH etching of (100) wafer with U-shaped mask → underetching of the mask and formation of inverted pyramids or 'roofs' with suspended mask beams



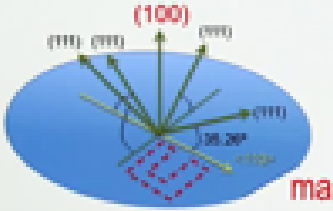
that are not attackable via other crystal planes, except for these two ridges, indicated by the green lines. At the top of these ridges, the silicon atoms that are fixed there, have less than three backbonds to the silicon, which is the reason why they are not so strongly bound and why these get attacked in the KOH bath. Therefore at the ridges, the etching continues, and the etching front proceeds underneath the mask

notes

summary

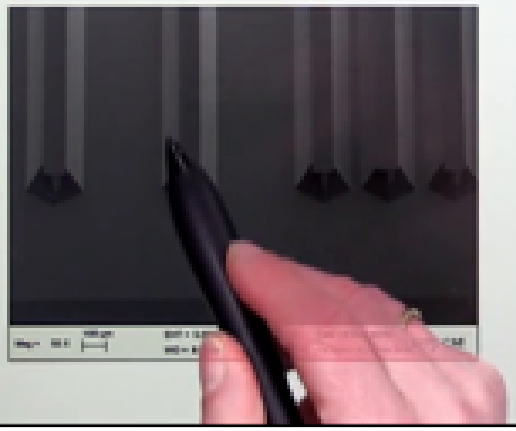
9m 19s

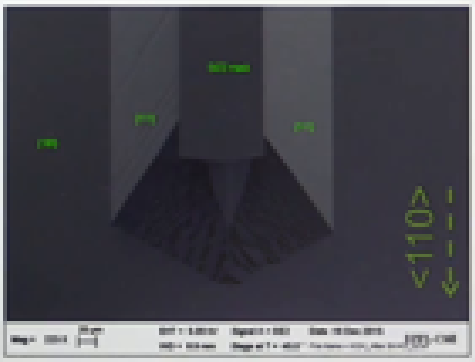
Bulk micromachining



mask opening

KOH etching of (100) wafer with U-shape type mask →underetching of the mask and formation of suspended mask (SiO_2) beams





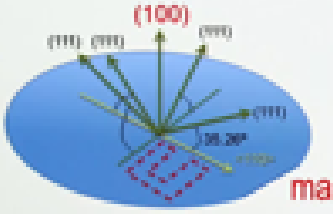
creating this suspended mask structure. At the same time, the etching proceeds also in the vertical direction so that the pyramidal hole gets deeper and deeper. This picture shows the situation when the etching under such a beam is proceeding.

notes

summary

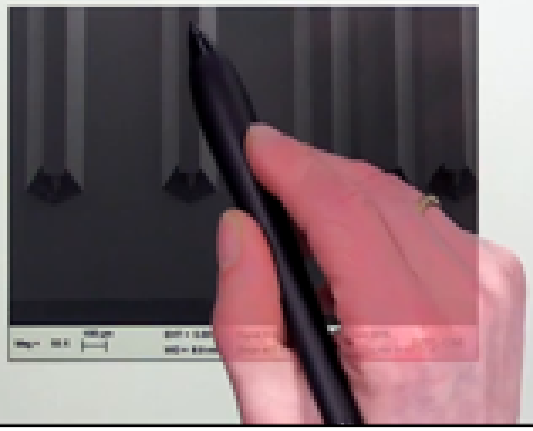
10m 1s

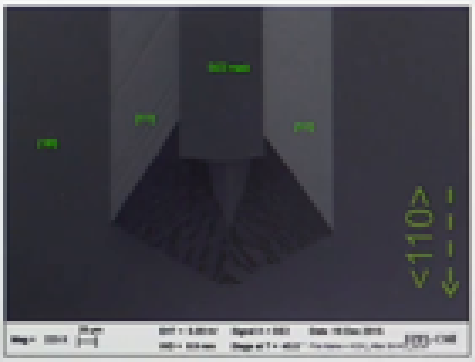
Bulk micromachining



mask opening

KOH etching of (100) wafer with U-shape type mask →underetching of the mask and formation of suspended mask (SiO_2) beams





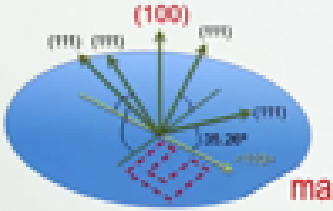
So here we have a mask beam.

notes

summary

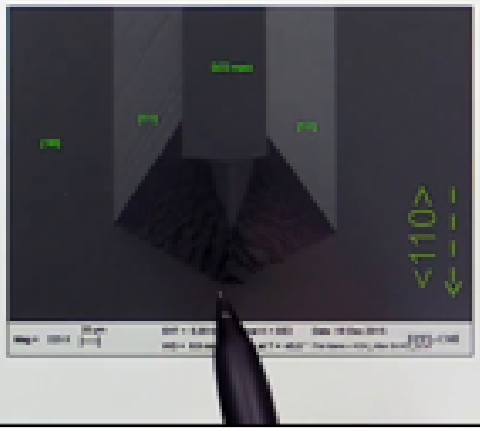
10m 25s

Bulk micromachining



mask opening

KOH etching of (100) wafer with U-shape type mask →underetching of the mask and formation of suspended mask (SiO_2) beams

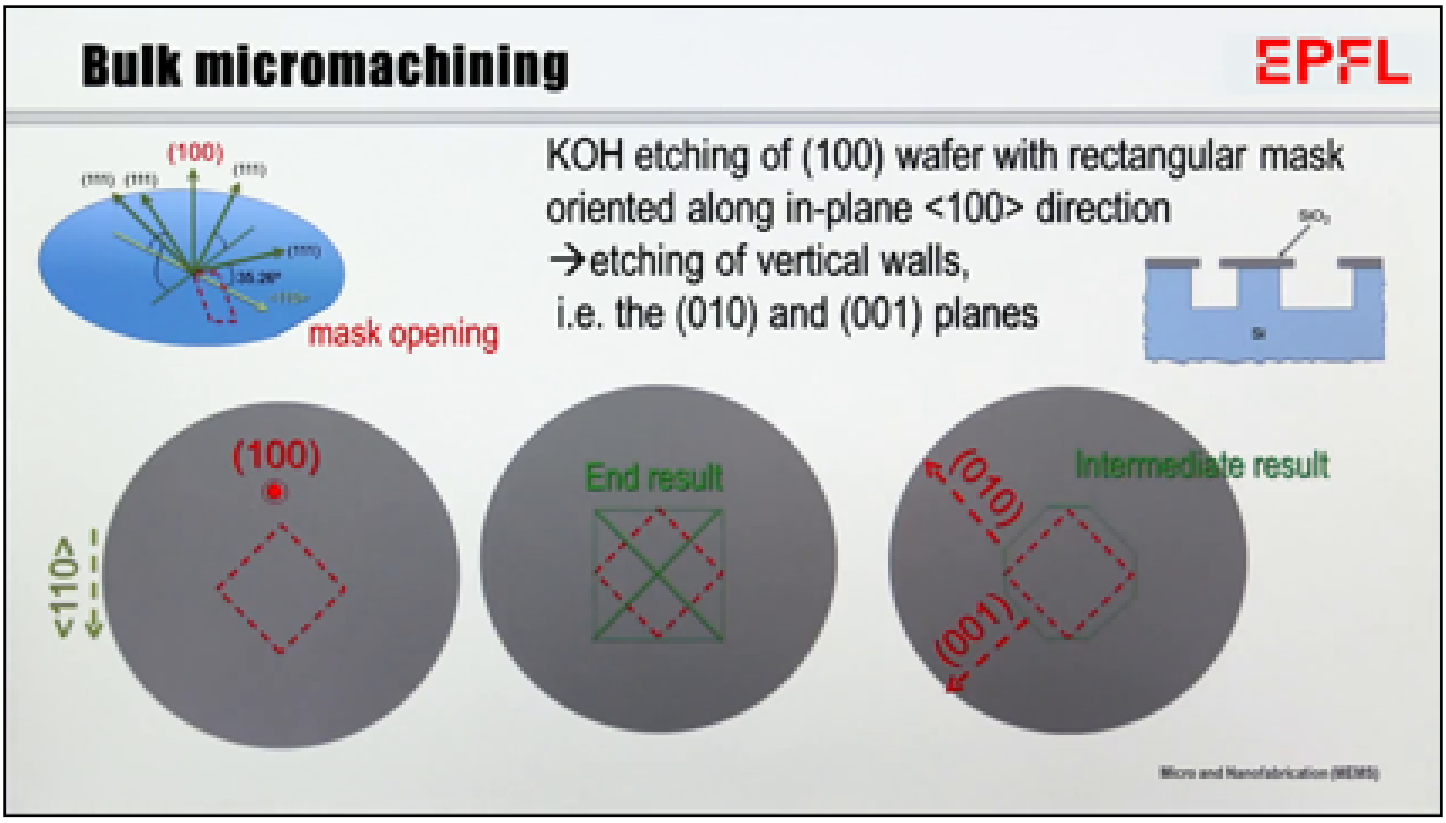


These are (111) planes, which are not attacked, but here there is attack on these planes. So this feature is magnified here. So you see here that the (111) planes will disappear at the end

notes

summary

10m 27s

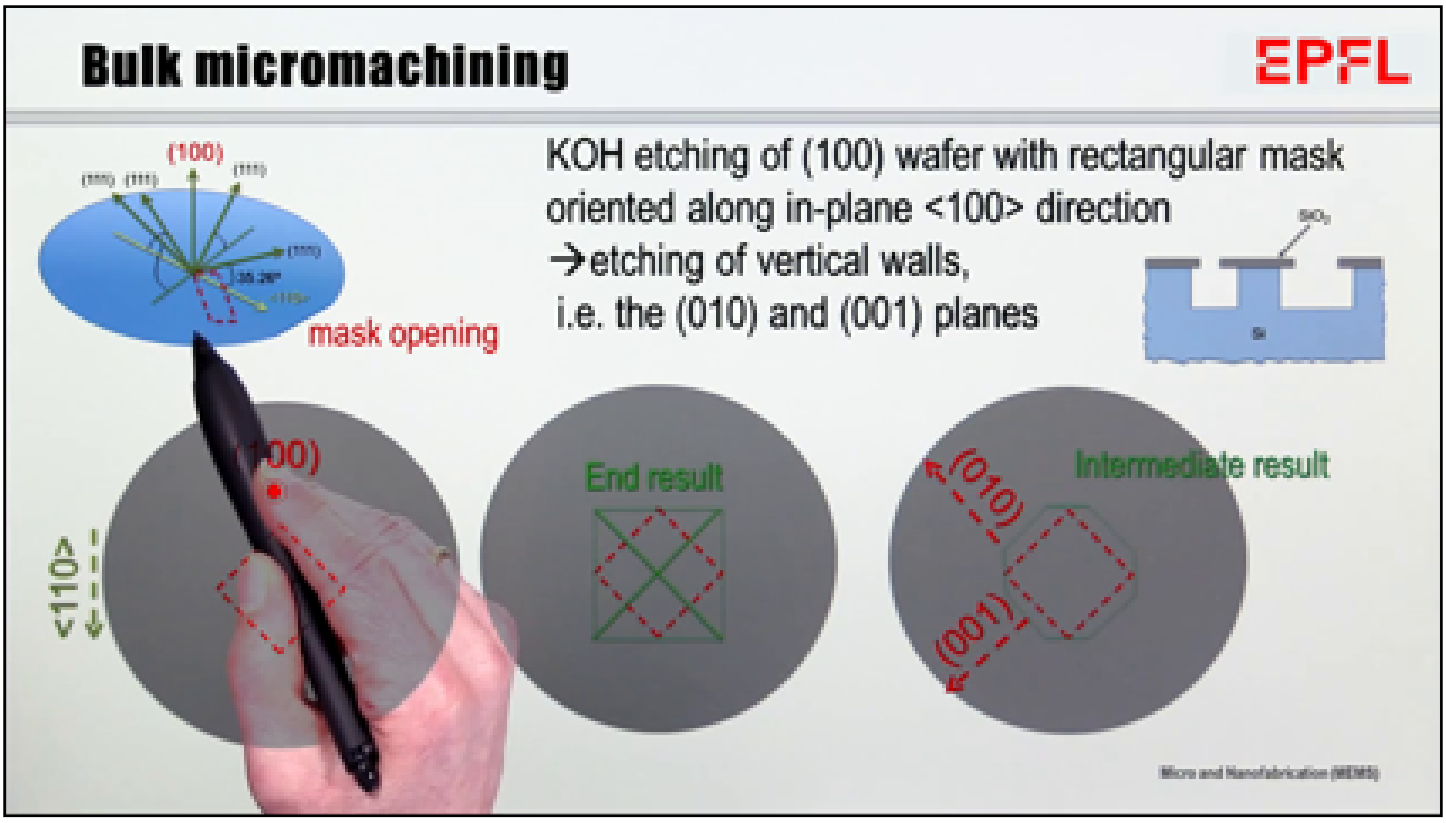


because the attack is going on by these planes here, and the complete silicon underneath the beam will be etched away like that.

notes

summary

10m 48s

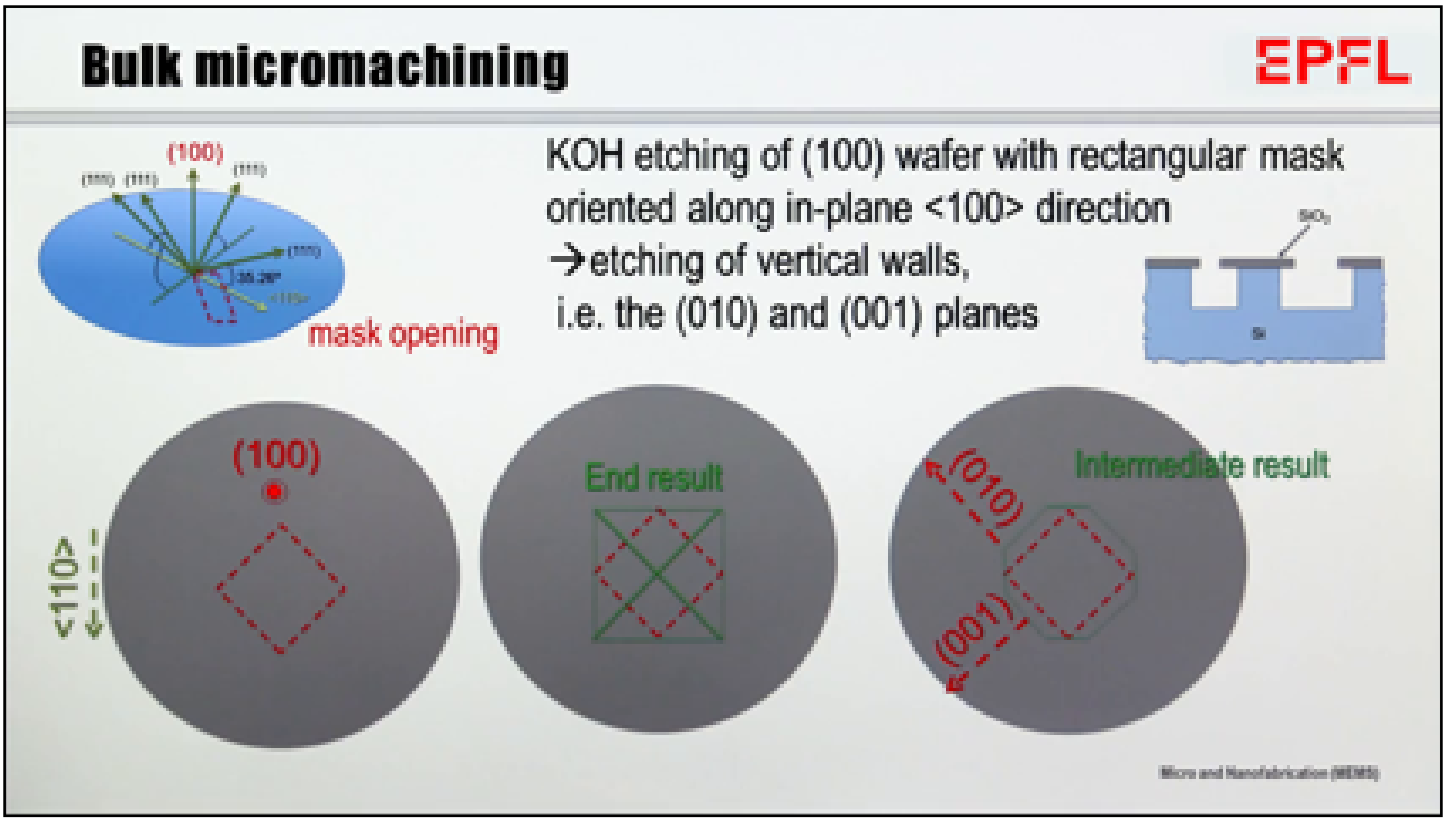


A last example of bulk micromachining is one in which one has again, a (100) wafer with a rectangular mask that has now been oriented

notes

summary

11m 0s

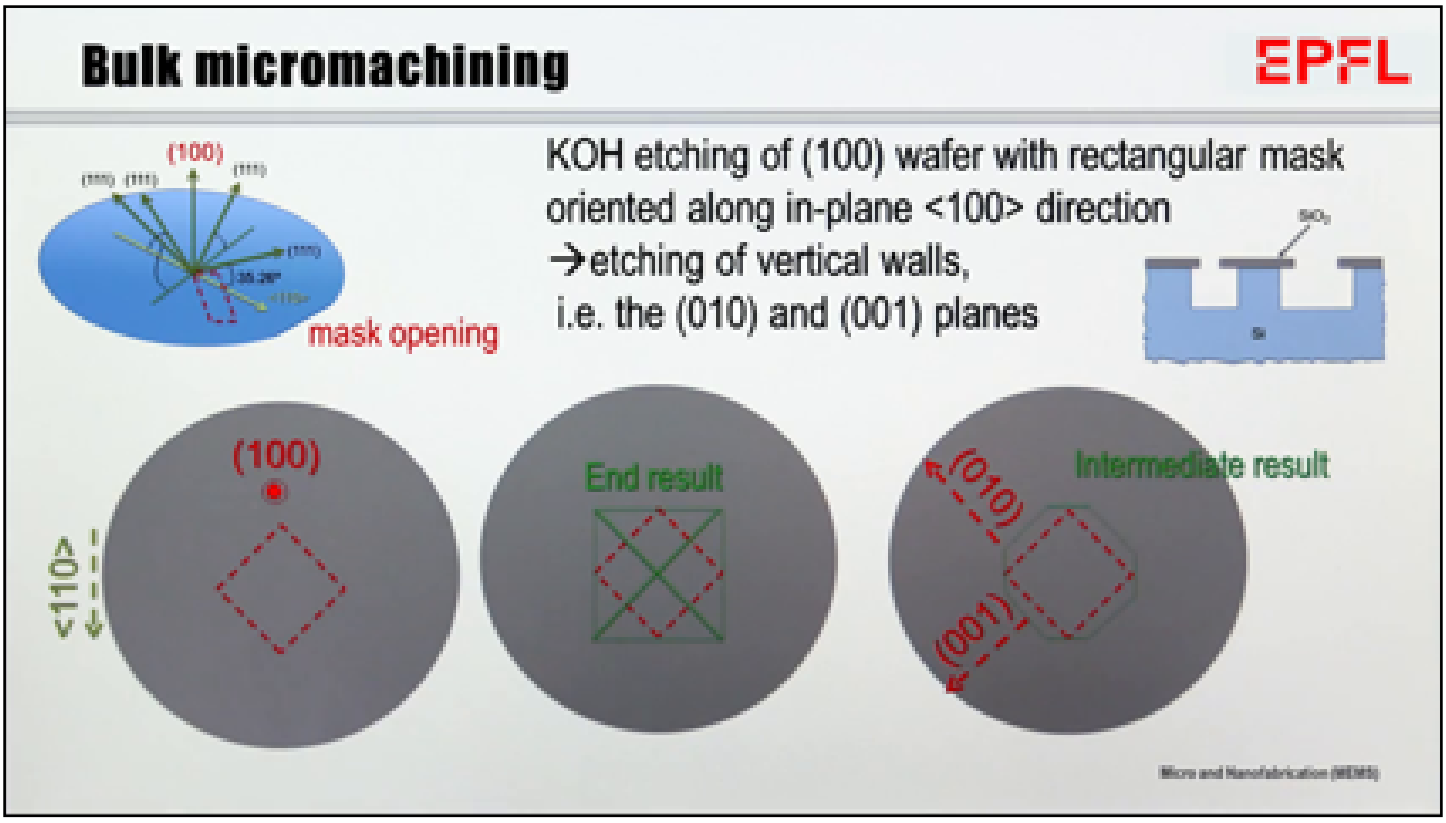


along an in-plane <100> direction. That means that this rectangle has been re-oriented over an in-plane angle of 45-degrees,

notes

summary

11m 11s



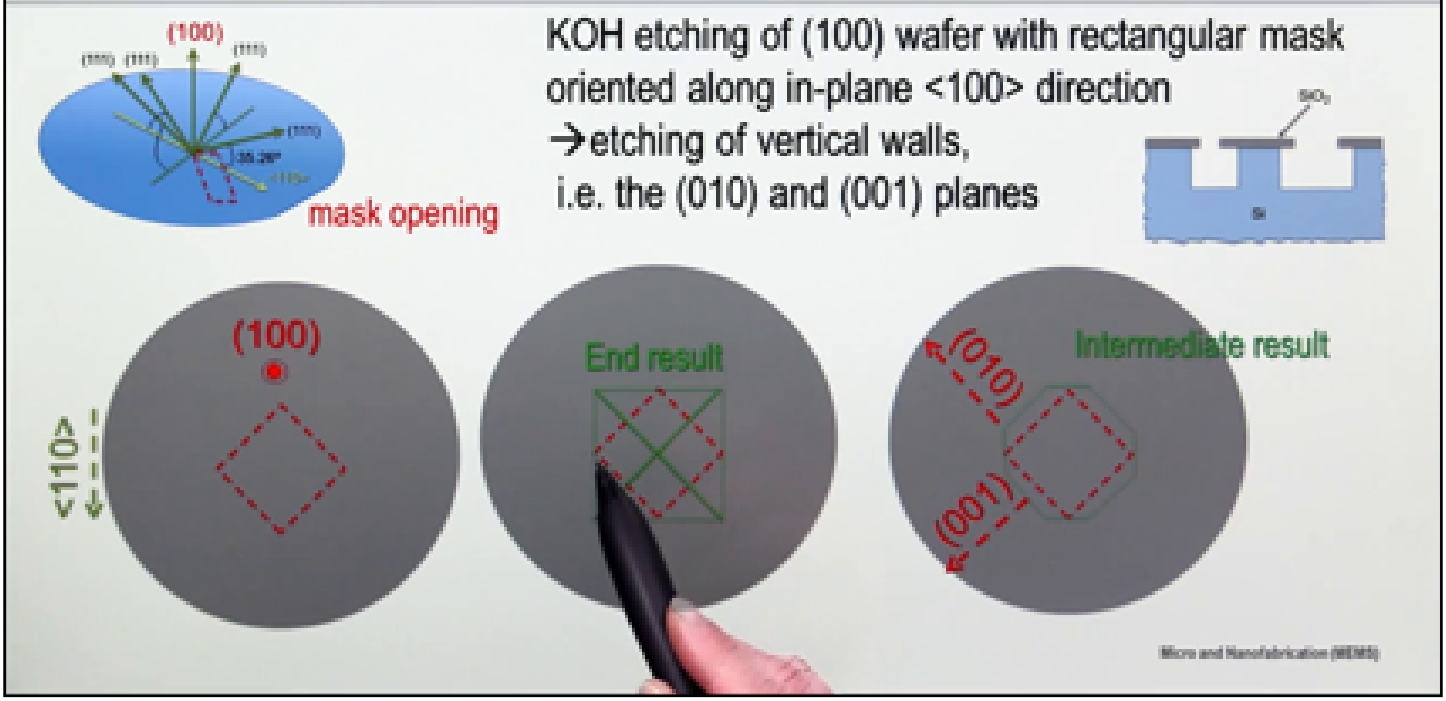
with respect to the initial rectangular mask we considered.

notes

summary

11m 25s

Bulk micromachining

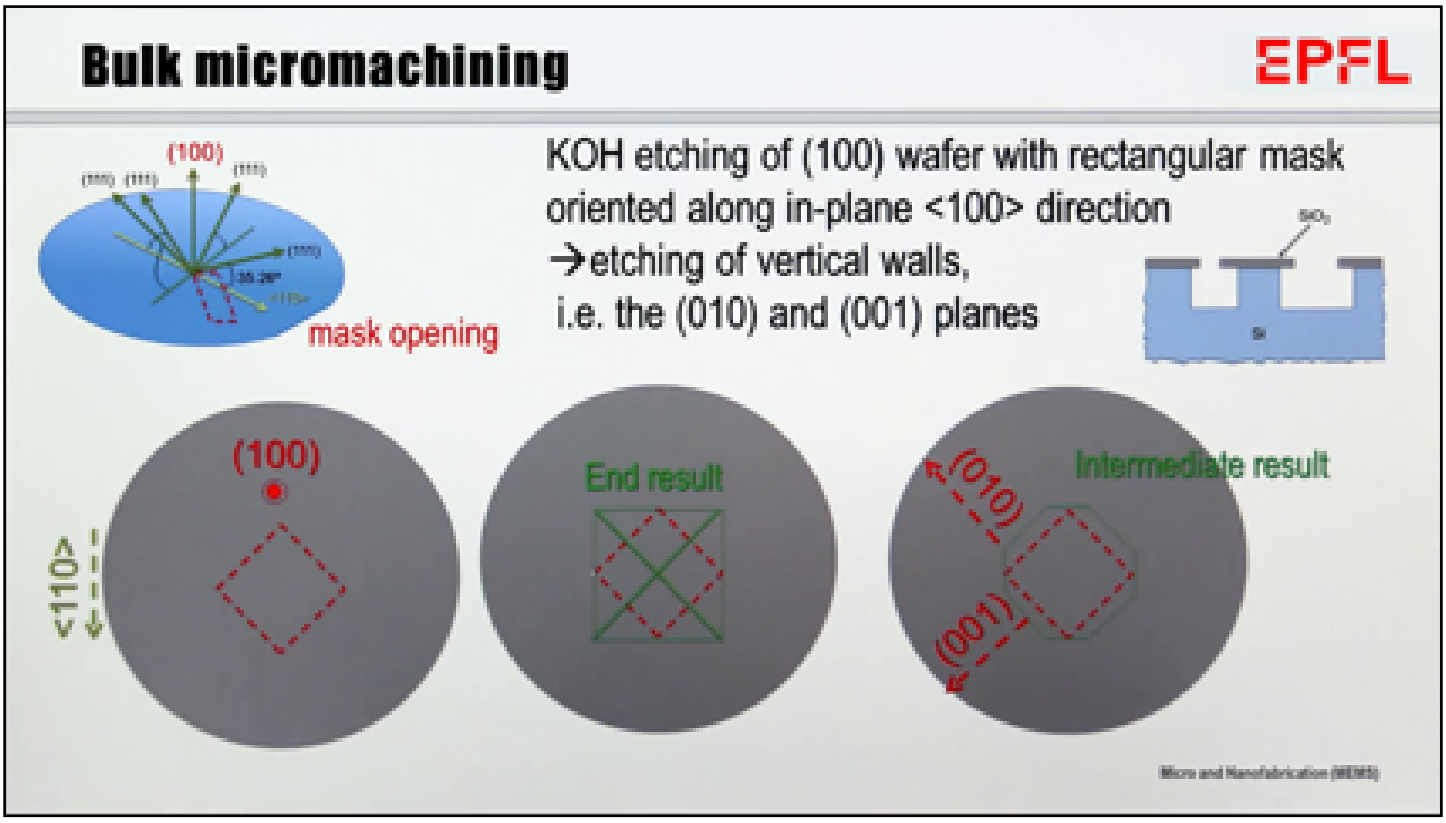


So this is the mask, this is the <110> direction, and we know that the end result will be an inverted pyramid like that. From the beginning of the etching,

notes

summary

11m 27s

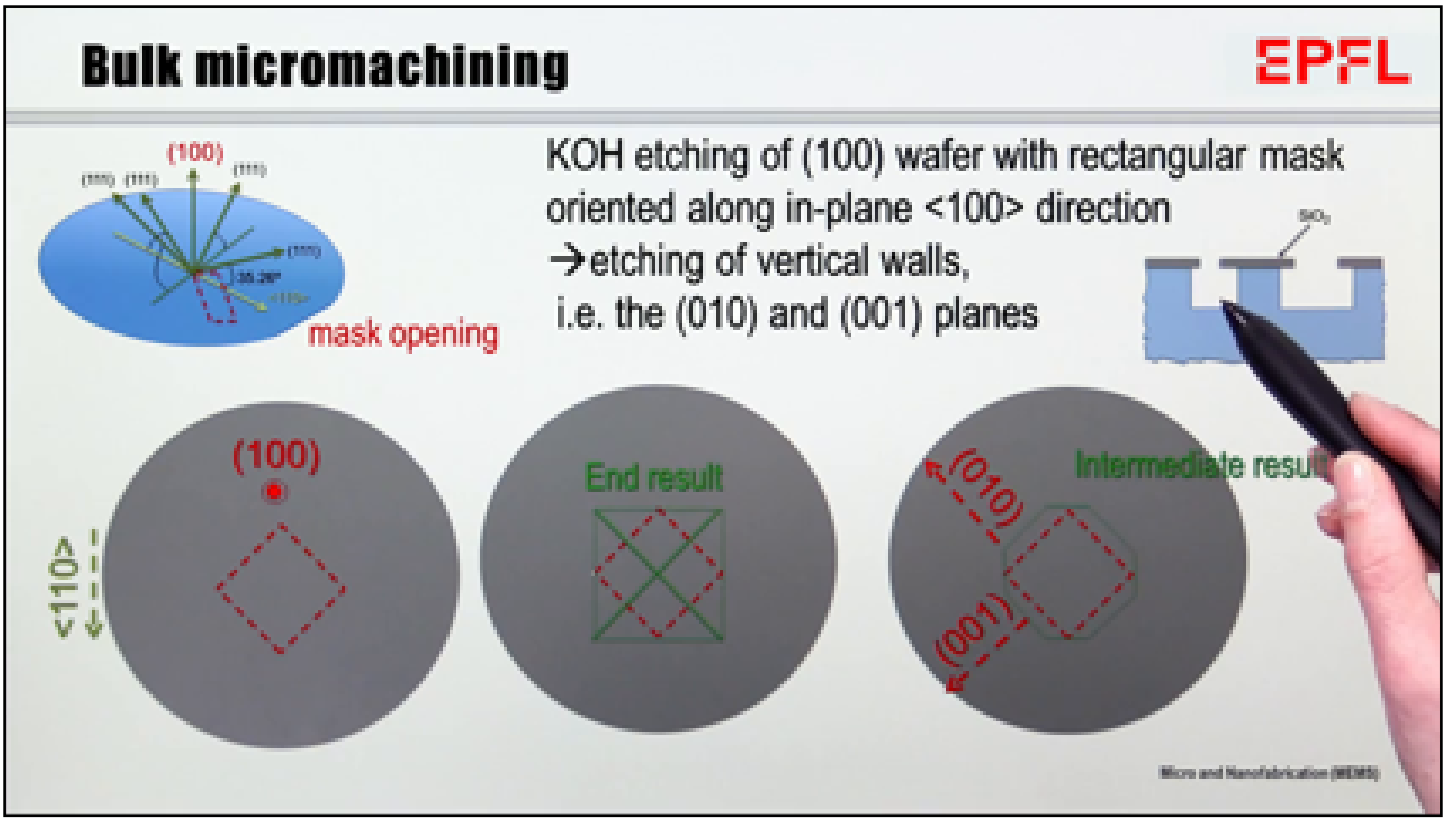


the (111) planes in these four corners will immediately appear and will not be attacked.

notes

summary

11m 47s

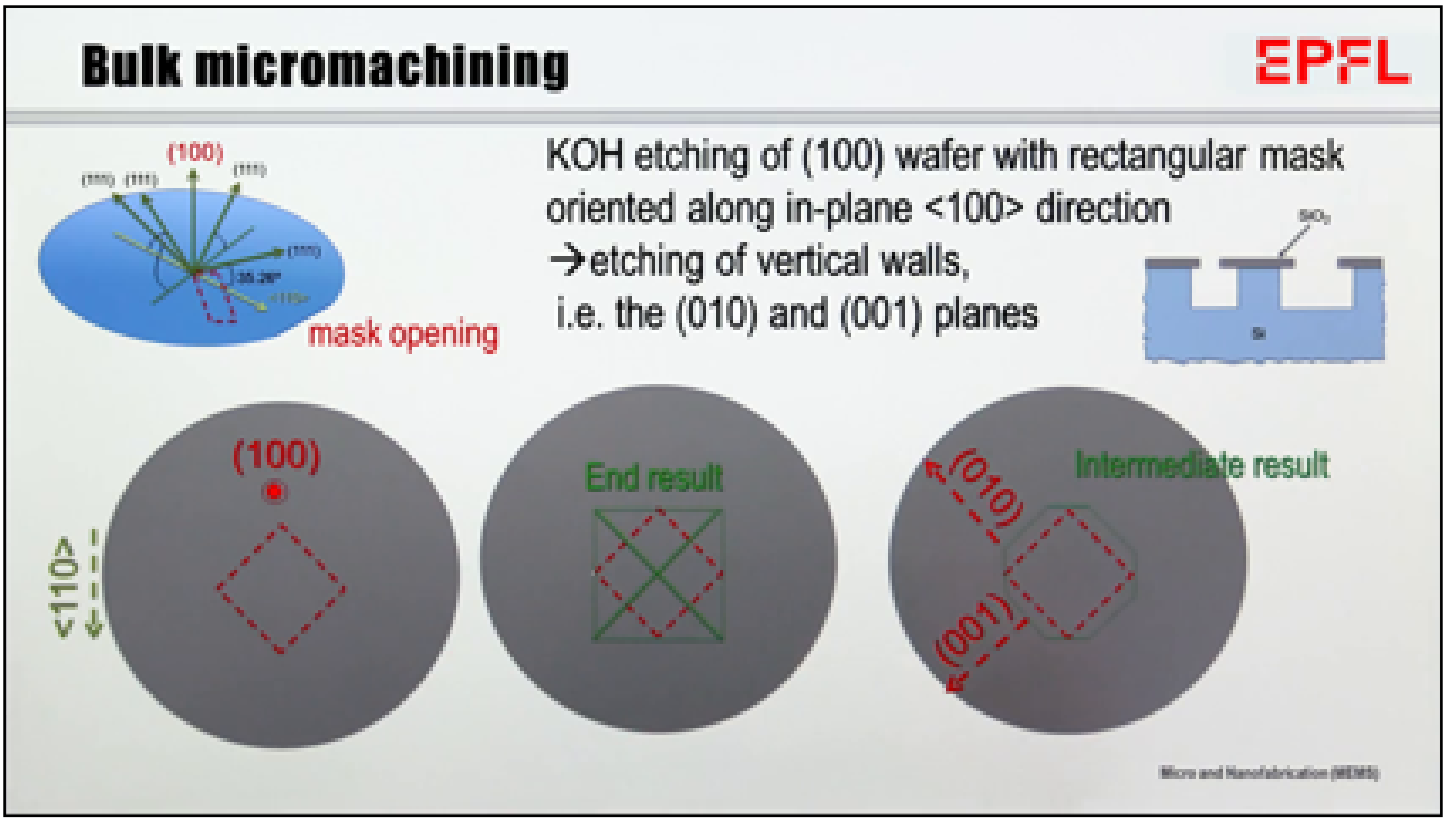


However, an interesting intermediate etching result appears, which is sketched in this cross section. Here one sees a hole that is etched, and a vertical plane, and this vertical plane, during etching,

notes

summary

11m 57s



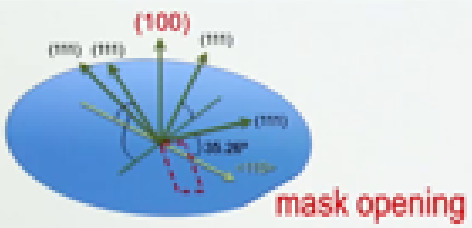
is going further and further underneath the mask. How can we understand this? We have here a (100) orientation of the wafer.

notes

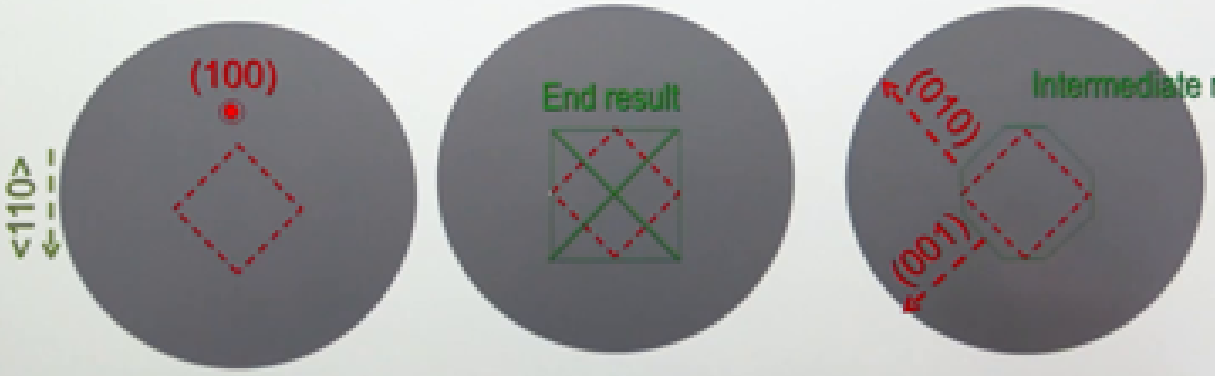
summary

12m 15s

Bulk micromachining



KOH etching of (100) wafer with rectangular mask oriented along in-plane <100> direction
→etching of vertical walls,
i.e. the (010) and (001) planes



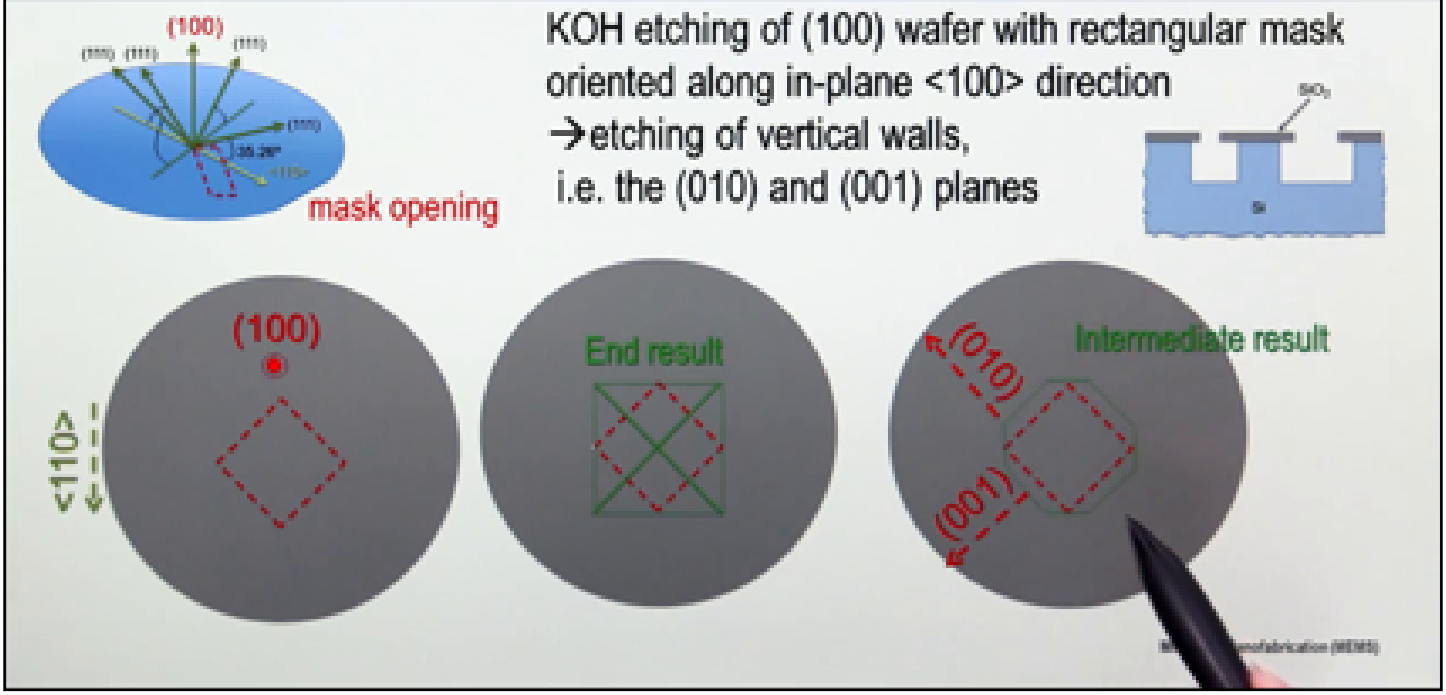
If we orient the square in the mask like this, this direction will be a (010) plane, and this will be a (001) plane.

notes

summary

12m 26s

Bulk micromachining

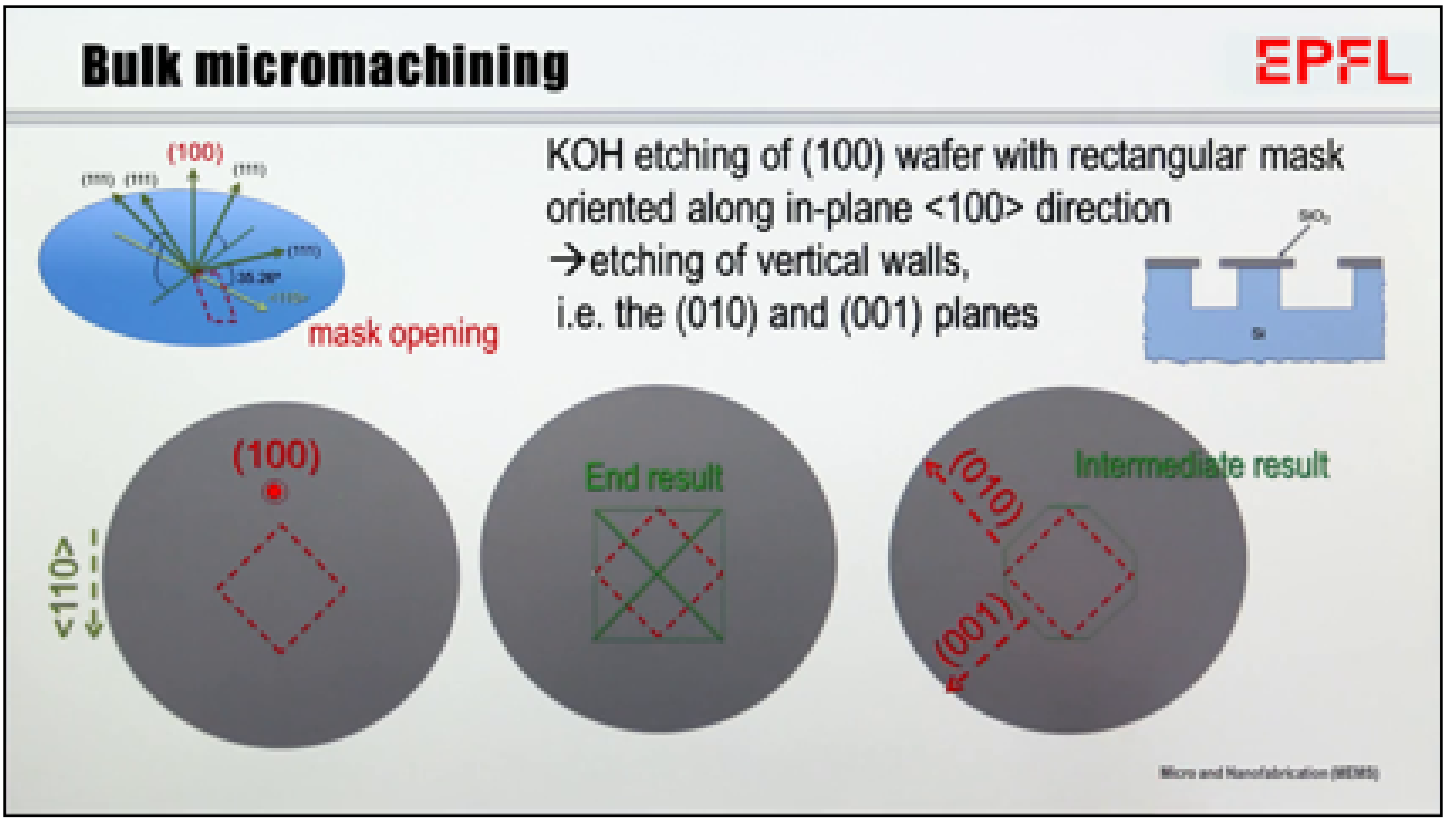


So that means that the planes are identical in the vertical and in the horizontal direction. So exactly the same etching rate, which will give such a rectangular hole. And these vertical walls, we see it here, and progessively the vertical holes will move in this direction

notes

summary

12m 39s

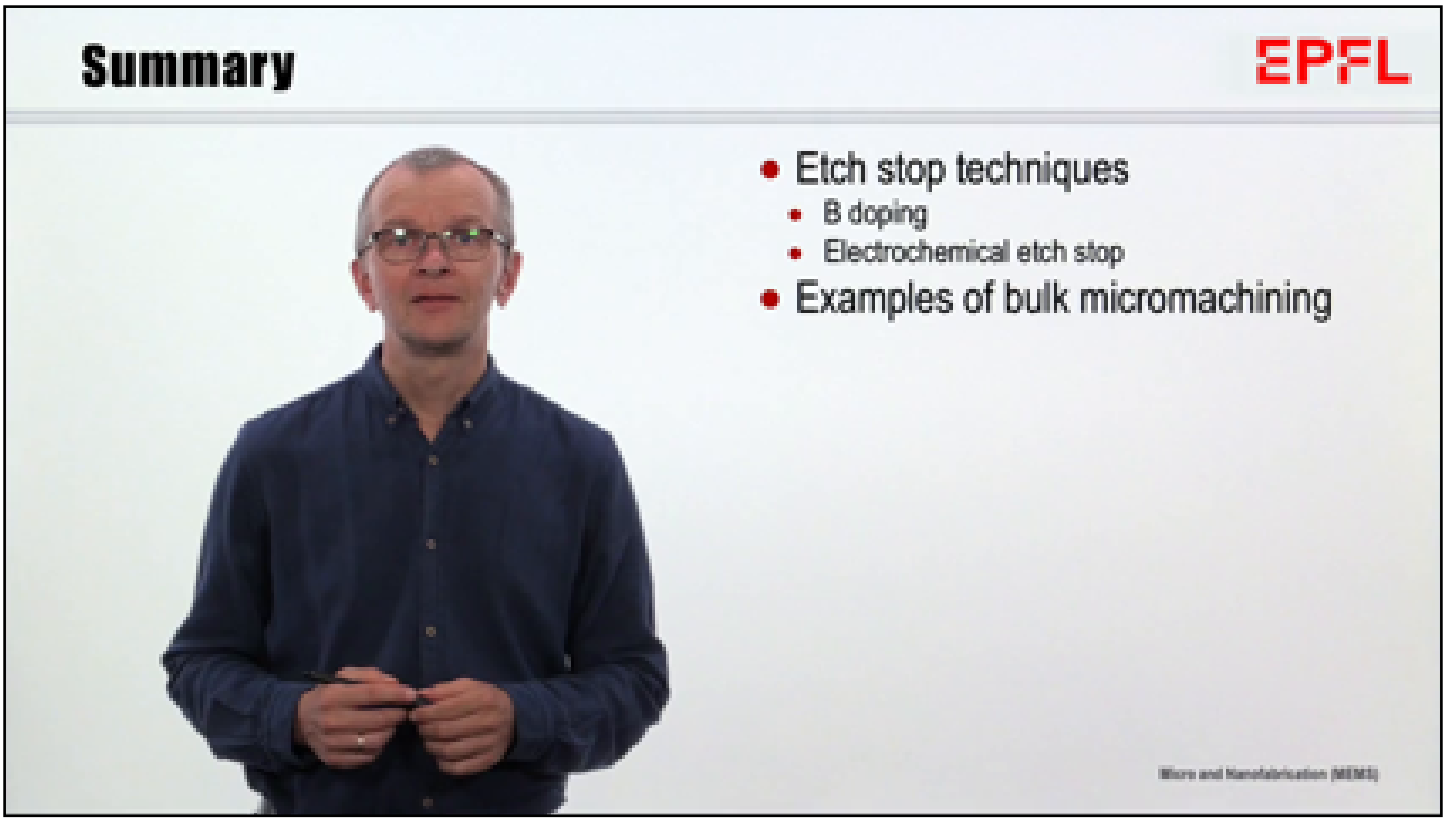


to the extreme directions. At the end, one will reach a (111) plane and if one waits long enough,

notes

summary

13m 1s



there will be only the (111) facets of the inverted pyramid which are visible. In this lesson we have discussed two etch stop techniques by which one can make very thin membranes. One etch stop technique was due to a heavy boron-doping, and the second technique was the eletrochemical etch stop exploiting the junction between lightly p- and n-doped silicon. Finally, we gave examples of bulk micromachining based on the orientation and shape of the mask on a (100) silicon wafer.

notes

summary

13m 8s