Biomedical Ultrasound: Fundamentals of Imaging and Micromachined Transducers

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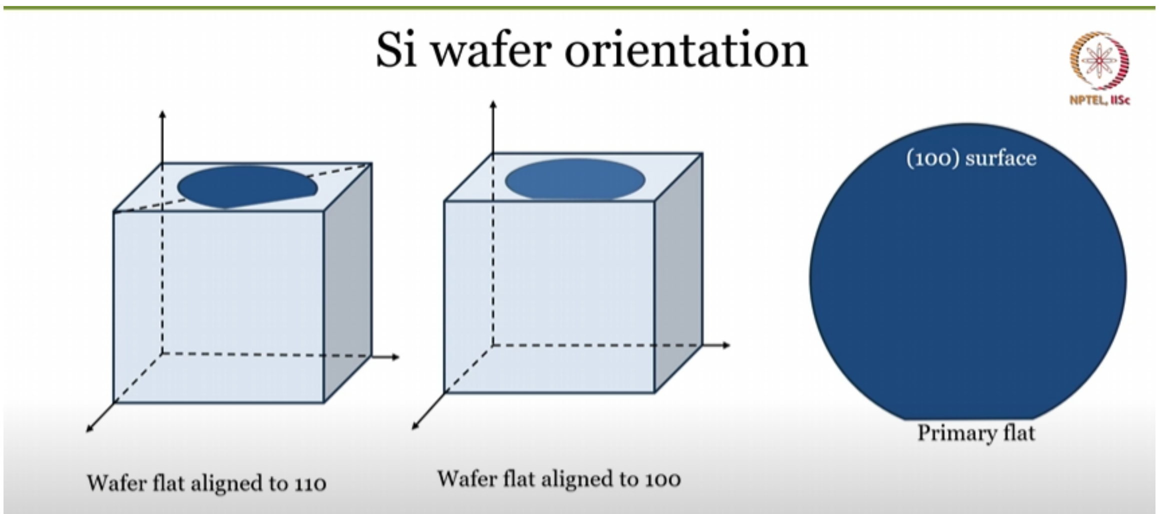
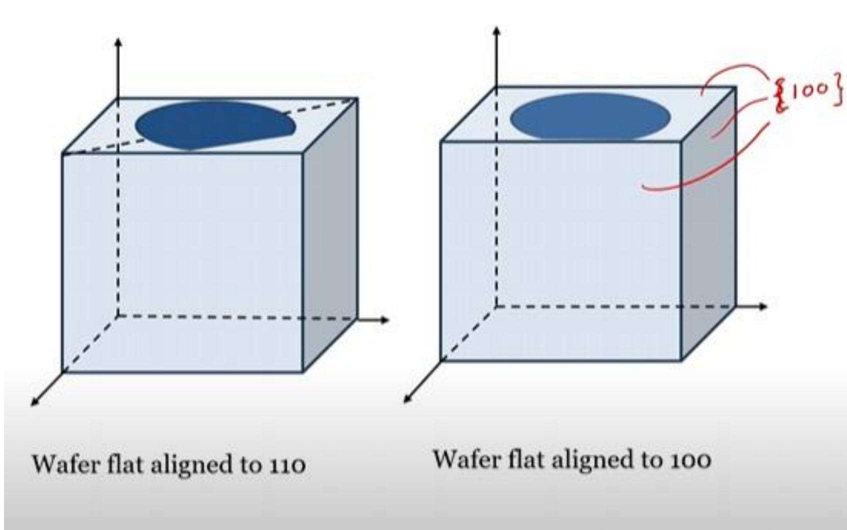
Lecture: 53

Wet etching and Miller Indices II

Hello everyone and welcome back to the session. So, in the previous part we saw what is etching and what are the different layers that one might need to etch, some characteristics to be kept in mind while selecting an etchant, and different types of etching such as isotropic and anisotropic, and most importantly what is Miller indices and which is important basically for an anisotropic wet etching. Today in this session we will see how this knowledge of Miller indices will help us in designing the proper mask, proper mask edges to get the different complicated shapes when we are dealing with anisotropic wet etching of silicon. So, let us get started. So, let us talk about the silicon wafer orientation.



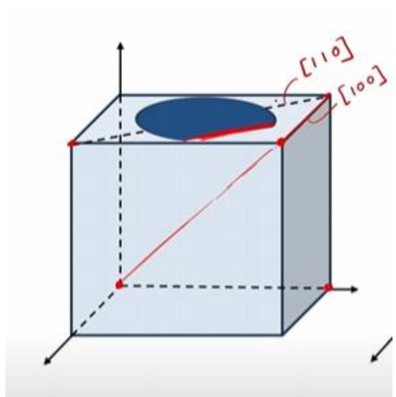
On the extreme right side, you see a schematic of silicon wafer which is basically a circle with a small primary flat. Now this primary flat is basically there to get an idea of what type of wafer we have. So, this surface will always be oriented to the 100 family of planes or 100 direction. This primary flat, along with some secondary flat will give you an idea about the direction, doping etc. So, if you see on the left I have two cubes aligned to the cartesian axis. Earlier while studying Miller indices, we learned that that the faces of cubes are basically giving us the family. Let us say the family of 1 0 0 planes



All the faces whatever you see are 1 0 0 family of planes. So, if you imagine your wafer to be aligned to one of these faces then you can say my wafer has a 100 surface because it is aligned to the 100 direction of plane.

Now, if you see the image on the left side, my primary flat is aligned to this diagonal, which is a face diagonal. A cube has two types of diagonals. If you join opposite corners of the same face, you end up with a face diagonal, and if you join the corners ofopposite faces, you end up with a body diagonal

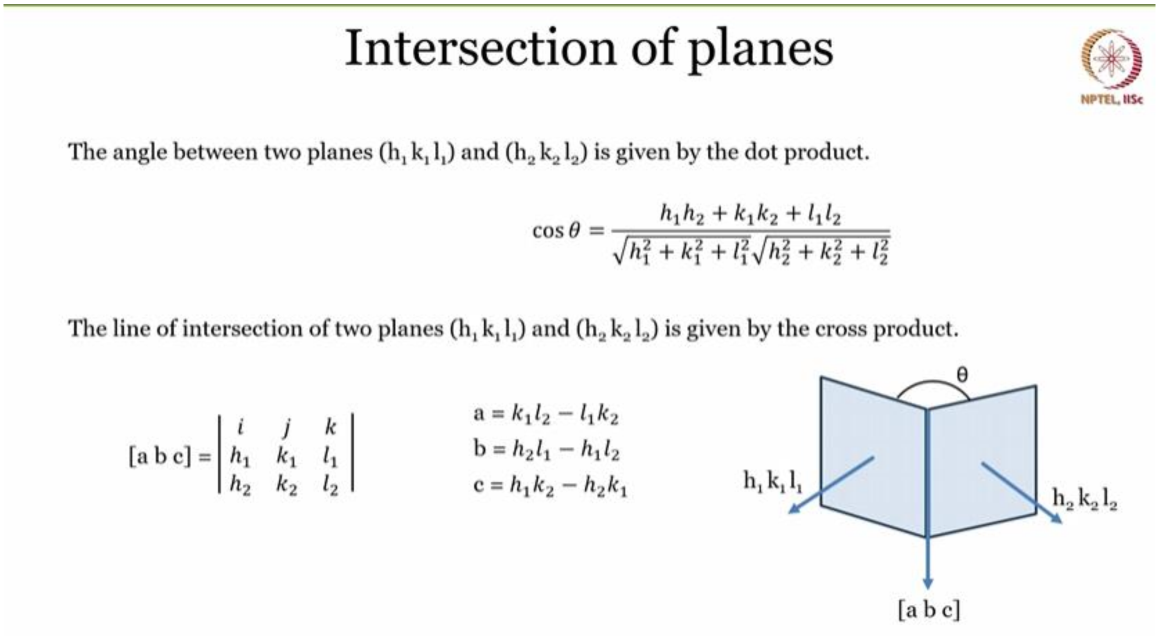
Okay, if you join these two points, let us say this is the origin and this is 1 comma 1 comma 1, then if you join these two points, it will become the body diagonal. Similarly, if you join these two points, okay, then again it becomes the body diagonal. The face diagonal is basically nothing, but the direction of [1 1 0]. We will see it in the subsequent slides how it comes to be [1 1 0]. But for now let us just say that it is actually [1 1 0] and if you talk about these edges, these edges have a direction of [1 0 0].



Basically, if we are talking in general we can say it might be [0 1 0] or [0 0 1] or [0 0 1 bar], but in this case the in general we will call them as [1 0 0] and we will call the faqce diagonal as [1 1 0] family of directions. So, we can actually represent them by <110 > notation because we are talking about the family and not just one direction.

So, if you talk about the edge, this will be <1 0 0> direction, and if you talk about the face diagonal it will be <1 1 0> direction and if you talk about any of the faces then it will be {1 0 0} family of planes. Now, if you see here, the primary flat of wafer is aligned to 110 in the first image, and it is aligned to 100 in the second image.

Now one important concept we will borrow from mathematics is the intersection of planes. Now let us say I want to find the angle between two planes. Let us say if you see the figure on the extreme right bottom.

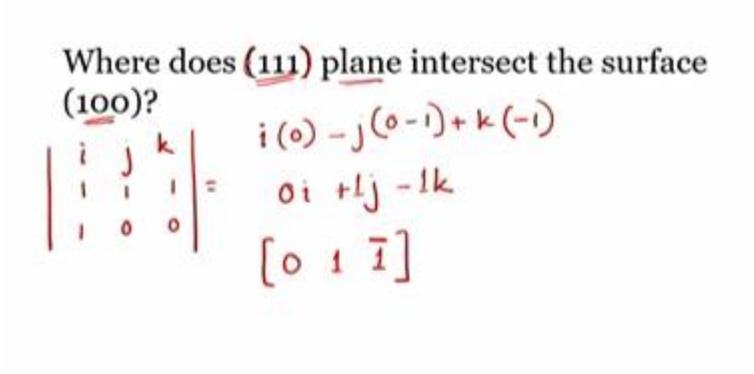


At the first glance it would look like you have opened a book. It is a good analogy if you open a book, you have basically two planes, plane 1 and plane 2. So, the direction of plane 1 is represented by h1, k1, l1 and direction or the normal of plane 2 is denoted by h2, k2, l2. And let us say these planes are intersecting at a line whose direction is given by the [a,b,c], and the angle between these two planes is θ. So, first we can calculate the angle theta between these 2 planes which is given by the dot product. If you see take a dot product you will have

$$cos\theta \ = \frac{h1h2 + k1k2 + l1l2}{\sqrt{h1^2 + k1^2 + l1^2} \ * \sqrt{h2^2 + k2^2 + l2^2}}$$

Now, from here you can get the angle. Now, same thing if you take the cross product you will get the direction [a,b,c].

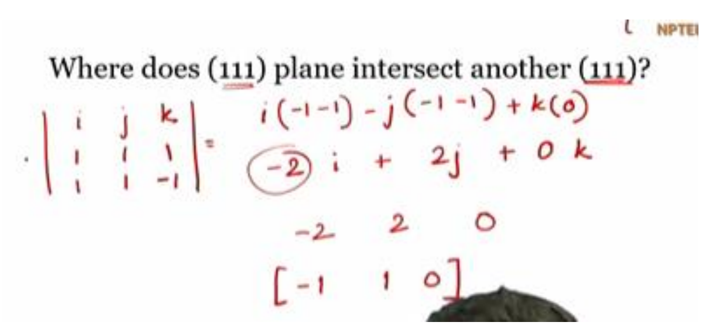
So, let us calculate some very important angles and directions which we will be using in the subsequent slides. So, I told you that there are 3 very important planes in silicon crystals, one is (1 0 0) then we have something called as (1 1 0) and also we have (1 1 1). Here I have (1 1 1). There are no commas in between and it is enclosed in a round bracket that means, I am talking about a plane.



So, I (111), and (100), and I want to know where do they intersect. So, I will take a cross product. How do you take a cross product is something like this. Aftrer cross product, you will get $[0\ 1\ \bar{1}]$ .What I am having here is a direction because if you intersect two lines you get a point and if you intersect two planes you get a line. So, this is a line or a direction, and I will enclose it in a square bracket. But, if let us say I have a family of planes, instead of a single plane, then I would get a family of directions, denoted by, <110 > . Now this is the first thing what you should keep in mind, wherever you see that my 100 plane is intersecting my 111 plane, that means definitely the direction would be a 110.

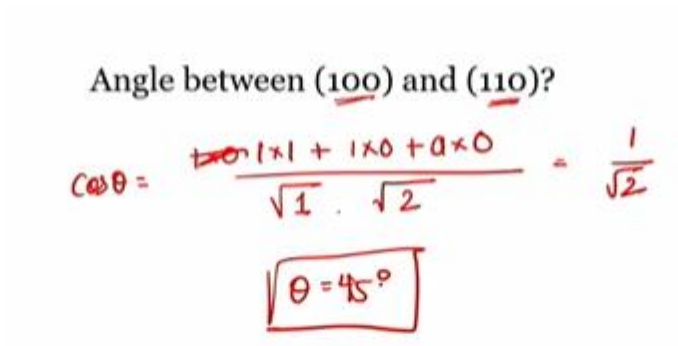
Now next thing is where does my (1 1 1) plane intersect another (1 1 1). Here, I am talking about a single plane, but essentially what I mean is what are the various combinations where any of the two planes from my 1 1 1 family would be meeting. So, if I do a cross product, I will get 0 because, if I am talking about the same planes basically they are coinciding, and I cannot say where are they intersecting.

So, I will use two different planes, let us say first I have (1 1 1) then I have (1 1 -1), which is basically the same family of planes. So, my cross product will be,

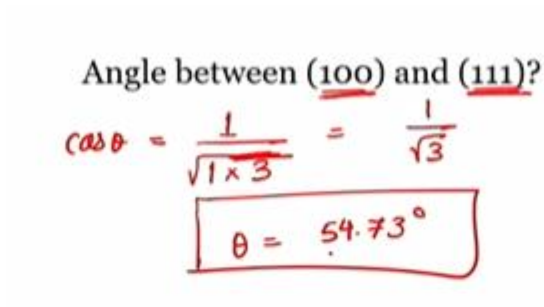


The direction I get is [-2 2 0] and now if I wanted to represent it using the lowest integers I will have [–1 1 0], which is the direction which I am getting for these two particular planes. But if I am talking about the possibility of a combination of all such planes, what I will get is a family of <1 1 0>. So, intersection of (111) with (100), and (111) with (111) are both in my <110> family of planes

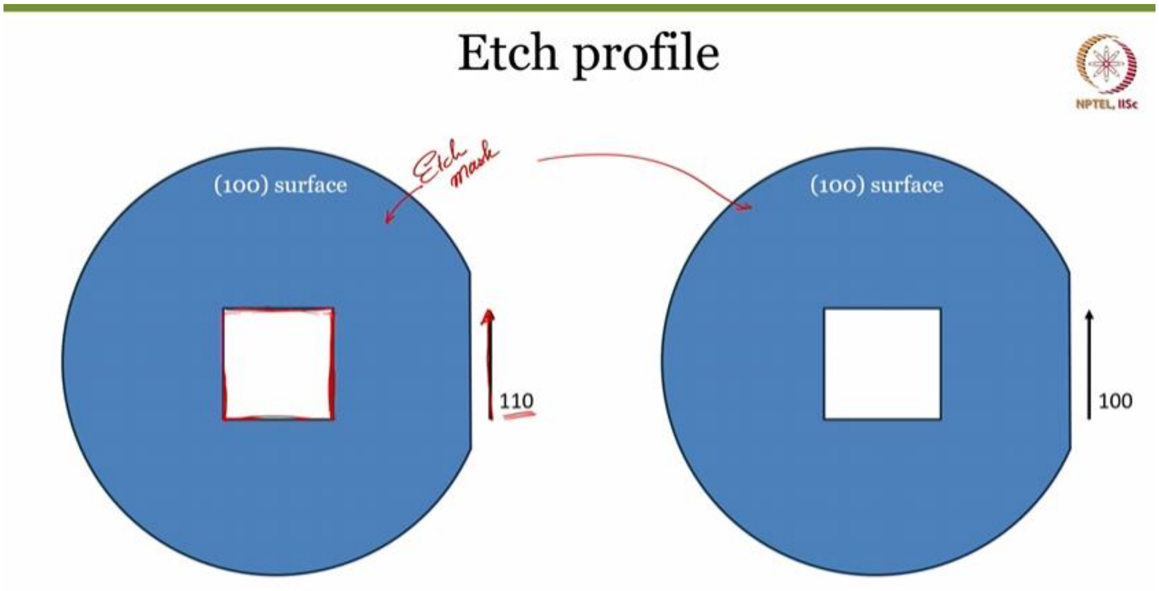
Now, let us use the dot product to find angles between two different planes. Let us say I have my (1 0 0) and (1 1 0). If you take a dot product, your final answer will be, $\theta=45^{o}$



Now, if you focus on the angle between 100 and 111 on the right side you will get $\theta=54.73^{o}$, after dot product. This might seem familiar because in one of the slides where we had not discussed about Miller indices but rather there was an image depicting the anisotropic etching of silicon, there this angle of 54.73 was present.



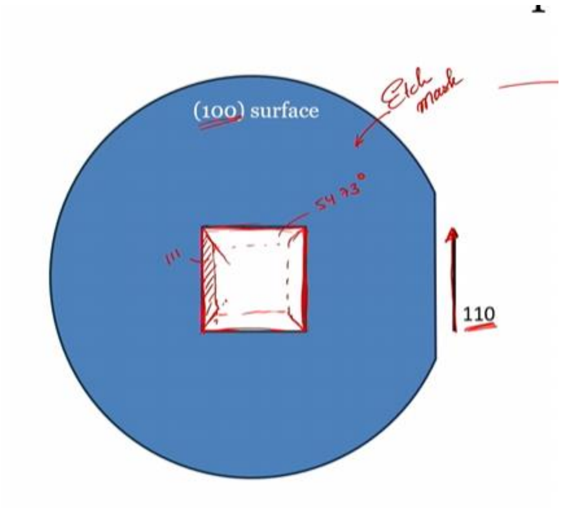
Now, let us move to another concept of etch profile. Let us say I have two identical shapes of silicon wafer, and I have a very small square opening, which is not to scale. Basically this blue region is the etch mask.



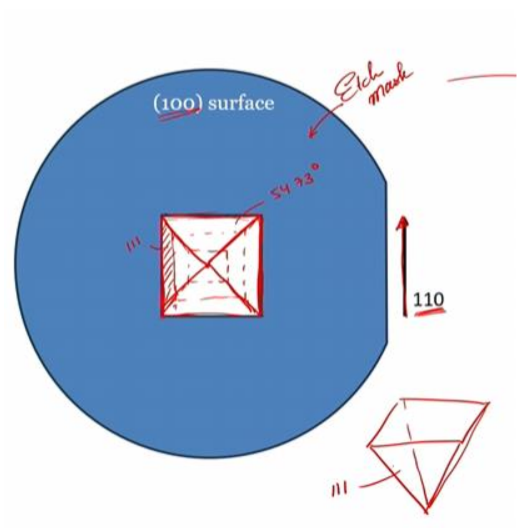
ok. This is the etch mask. So, let us say I am using KOH to etch silicon and the white region that you see in between is the exposed silicon and the blue region is the etch mask. Let us say silicon nitride or maybe oxide and my KOH will not affect it. Let us assume that. So here, my wafer flat is is 110. So this direction will also be 110 and also all these directions what you see over the whole square will also be 110. how do we know that because previous in the previous slide we calculated that the angle between 100 and 110 direction is actually 45 degrees.

So, if you see on the right side, I have my 1 0 0 direction. So, all these directions of edges of this square will be actually 1 0 0 direction. Now, if you coming back to the left side, if you remember the etch stop for silicon etching is basically a 1 1 1 plane. So, where does my 1 1 1 plane actually intersect my surface. So, what I need to essentially calculate is where does my 1 0 0 surface intersecting the 1 1 1 plane.

In the previous slide we have here calculated that my 1 0 0 surface or plane will intersect my triple 1 plane at <1 1 0> direction. So, here it is pretty straight forward because I already have my 1 1 0 marked out. And, once the etching starts, my etching will finally look something like this.

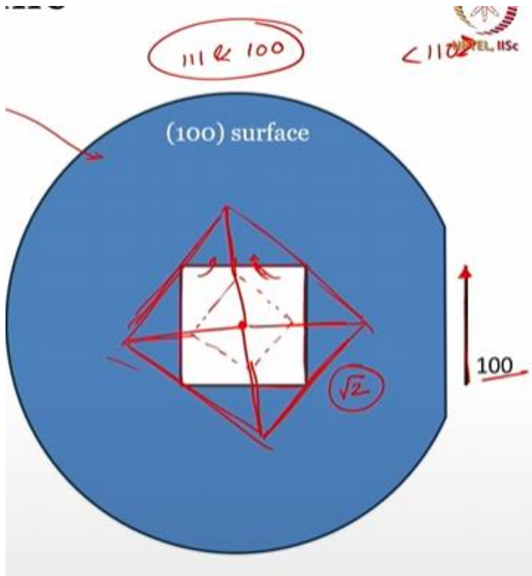


The etching will start converging at an angle of 54.73 because that is the angle between my 1 1 1 plane and 1 0 0 surface. So, if you see it from the top it will keep going forward in the downward direction at an angle of 54.73, and finally, when the etching is stopped, the plane is 111 and etching will not continue in this direction. But it will go keep going down in the downward direction. Finally, what will happen is this etching will keep moving forward and this square that you see will keep getting smaller and smaller to the point where I have a pyramid shape somewhat like this.



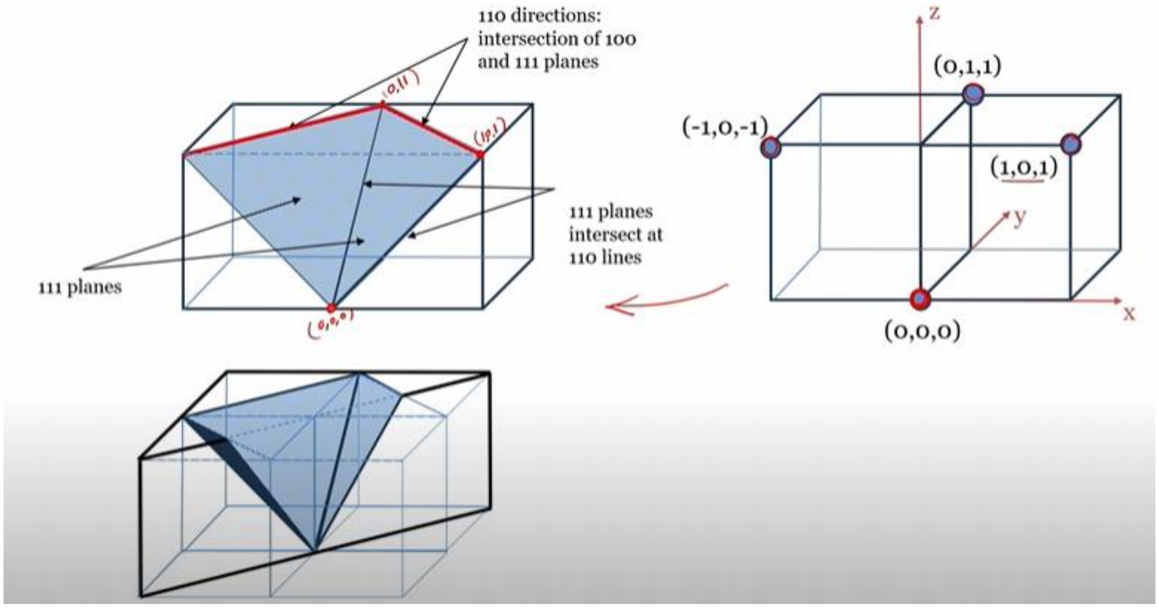
I will have a pyramid shape and all these planes 4 planes which are making this pyramid will be 1 1 1 planes.

And you will be getting a similar shape in this second case because it is 1 0 0. We will actually need to calculate where does my 1 1 0 direction lie. Because this is the direction where my 1 1 1 plane and my 1 0 0 surface will be intersecting. So, previously we also saw the angle between this 1 0 0 and 1 1 0 plane or the direction in this case in both the cases it will be 45.

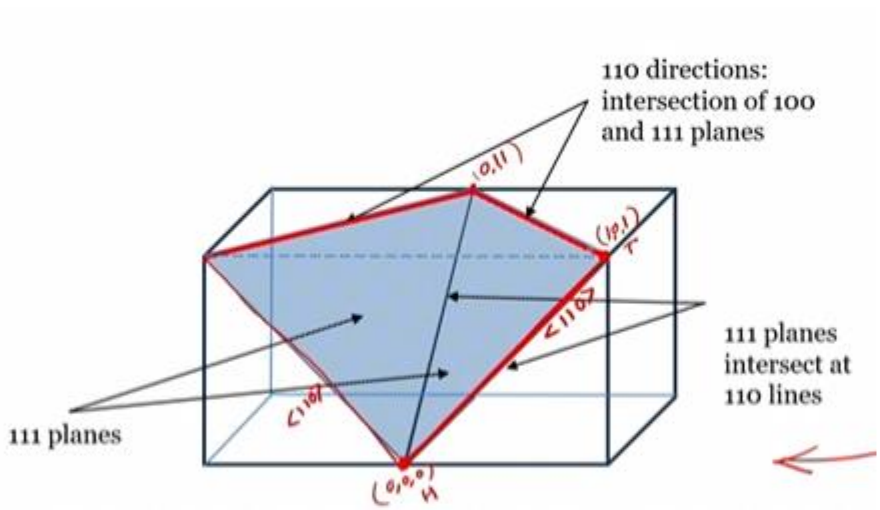


So, we will have something like this at an angle of 45 degrees to this square. We will have another larger square, and finally we will have something similar from the first case, but the square will be a little bigger and the reason here is because once this etching starts my etchant will also go inside, below this mask and start carry out the etching process because there will be a gap and my etchant will start ingressing inside this cavity and the entire part will be etched, till it sees that 100 direction. And finally, here also we will have a pyramidal cavity. The mechanism of reaction remains the same. The only thing is because my mask was not aligned to the 100 direction properly, rather it was in the direction of 100 and not 110. So, the final cavity will be a little larger and to be precise it will be root 2 times larger or 1.414 times larger than the desired cavity.

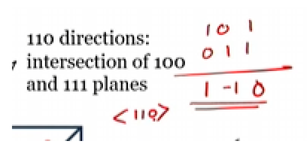
Let us move forward. Now on the right side I have 2 cubic cells and I have marked a few lattice points. And, if you see these 2 cubic cells it will be a little easier for you to visualize this plane which I am talking about. The same thing I have kept it here on the left side.



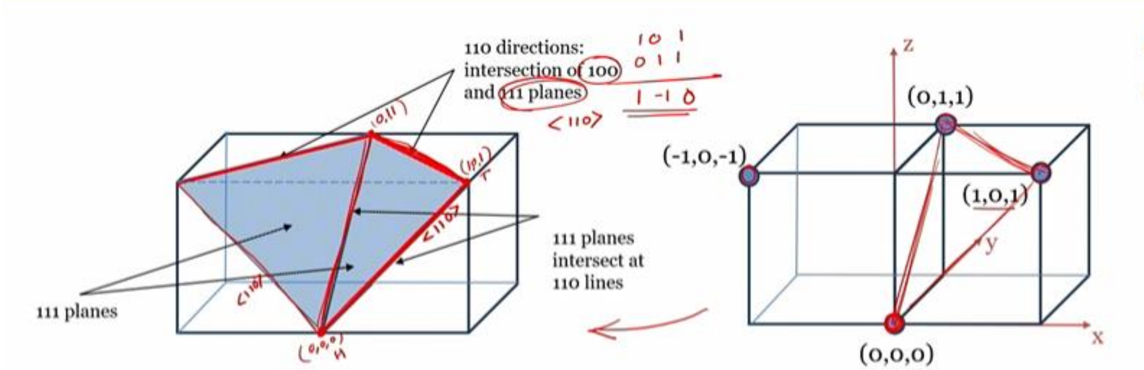
Now tell me what would be the line joining (0,0,0) and (1,0,1). So, if you remember the Miller indices of directions, the idea was to subtract the tail coordinates from the head coordinates. So, this gave us the direction of 1 0 1, but this 1 0 1 is basically the family of <1 1 0>. And similarly on the line joining (0,0,0), and (-1,0,-1) also, you will get is the family of <1 1 0> .



If you talk about the line joining (1,0,1) and (0,1,1) is also the family of <1 1 0>. How do you get it is, we can always subtract the tail and head coordinates and see the direction. So you will get 1 -1 0, which is the same family as <110>,

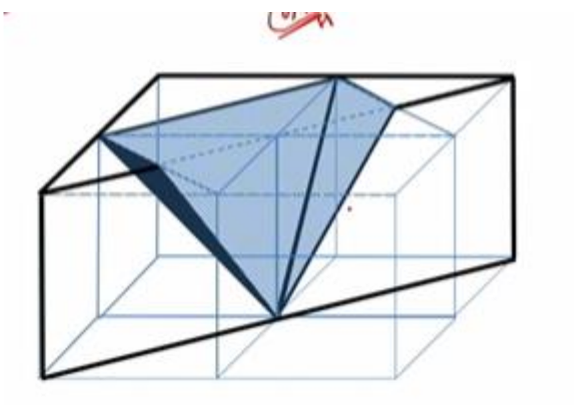


So we are proving it here that this top face is basically 1 0 0 and this plane joining (0,0,0), (1,0,1), and (0,1,1) is my triple 1 plane where my etching is actually going to stop. How do I know that this is my 1 1 1 plane is because if you connect these 3 points, you get something like a triangle and previously we saw by connecting these 3 points the triangular region that we are getting is basically a 1 1 1 plane.

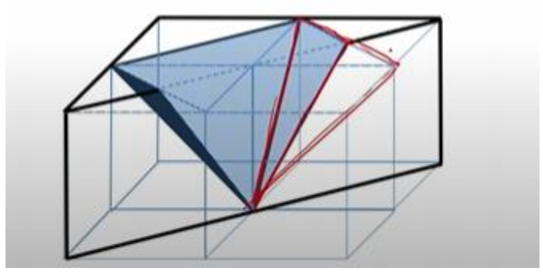


So, now we can see that these were the two, 1 1 1 planes (highlighted in blue) and where these two, 1 1 1 planes are intersecting has a direction of <1 1 0>. And the 1 1 1 plane is actually intersecting my 1 0 0 face at this <1 1 0> direction as well.

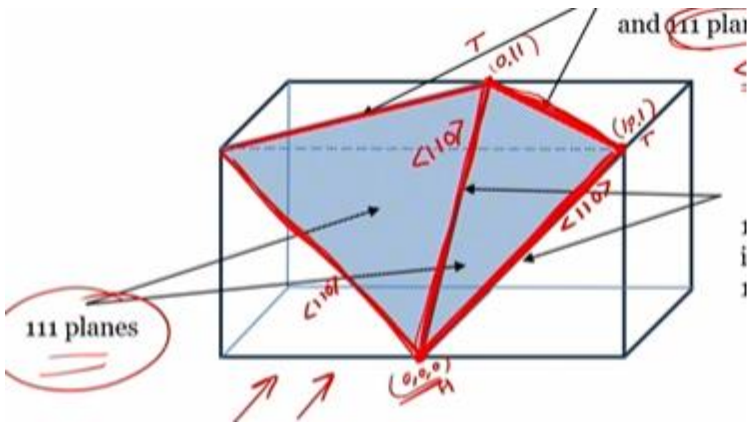
Now let us see the figure below.



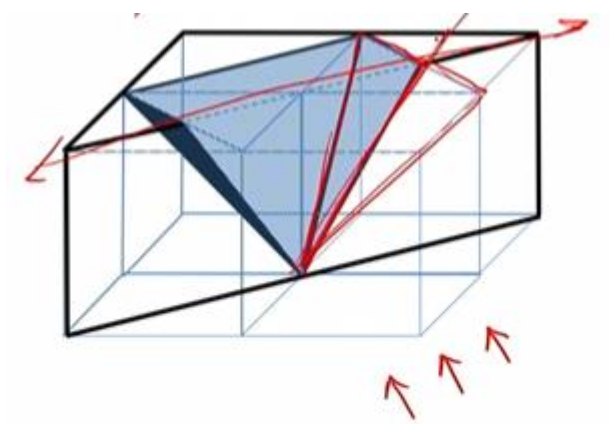
In this figure also, everything remains the same and the only thing that changes is that the cross section which I am taking is a little different. So, if you see this small trangle is a cut out from the larger triangle or larger 1 1 1 plane.



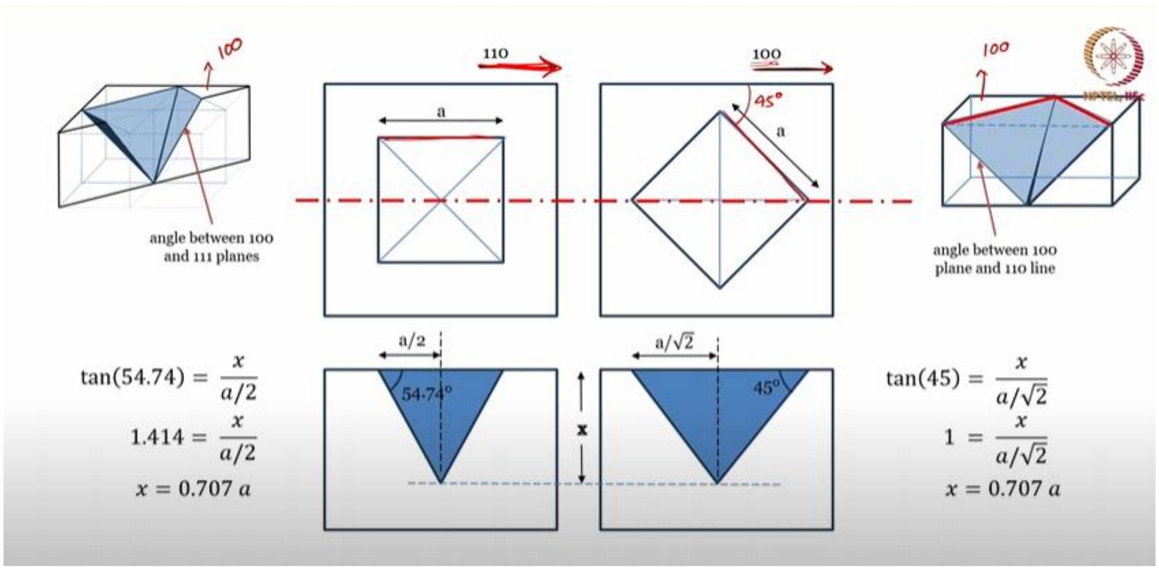
So, what happens when you see the below figure from the direction marked with arrows is that what you see is not actually the cross section of the 111 plane, but I am seeing two, 110 lines.



But, if I take a cross section along this line and if I see from this angle as below, what I am essentially seeing is a cross section of the 111 plane. These are the two different things if you see.

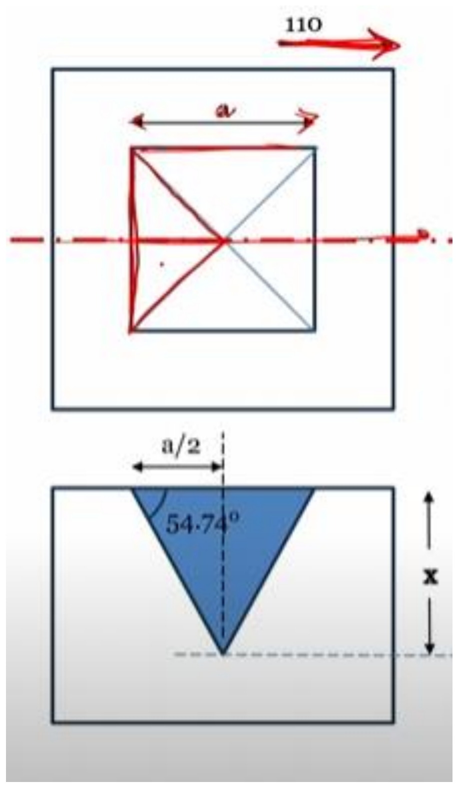


We will see in the next slide how does it matter how does it affect your calculations. Let us see here on the left side I have the face which is definitely still 1 0 0. In both the cases my silicon surface is 1 0 0, but the mask edge on left it is aligned to 1 1 0 and on the right, the mask edge is again aligned to 1 1 0. How do I know that, because this is at a angle of 45 degree with 1 0 0.



So, both the mask are identically and have an edge length of a in both the cases. So, essentially if the mask edge is aligned to 110 direction and the edge length is same, then whatever shape you get should be one and the same. And I will prove how it is actually same, but depending upon from which angle or cross section you are viewing the calculations might differ a little bit.

So, let us say in the first case it is quite clear that here if you cut it from here, basically what I am having is a cross section of my 1 1 1 plane.

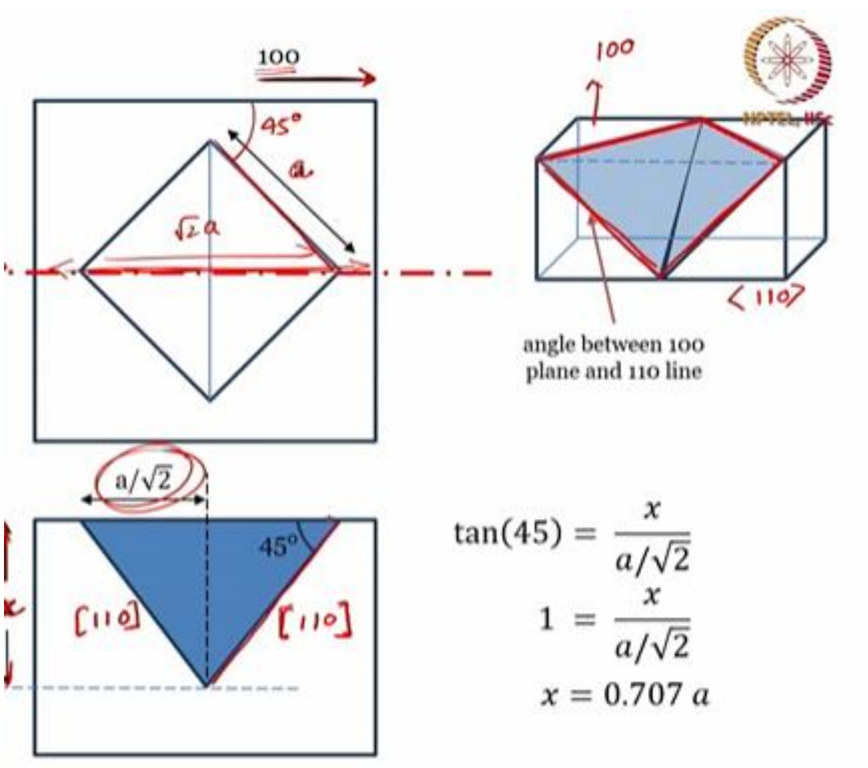


So, here if you see this angle this angle comes out to be 54.73 because this direction is between 100 and 111. So, now, if I want to calculate the value of x, I will take a tan of x.

$$\tan(54.74) = \frac{x}{a/2}$$
$$1.414 = \frac{x}{a/2}$$
$$x = 0.707\,a$$

And x comes out to be 0.707

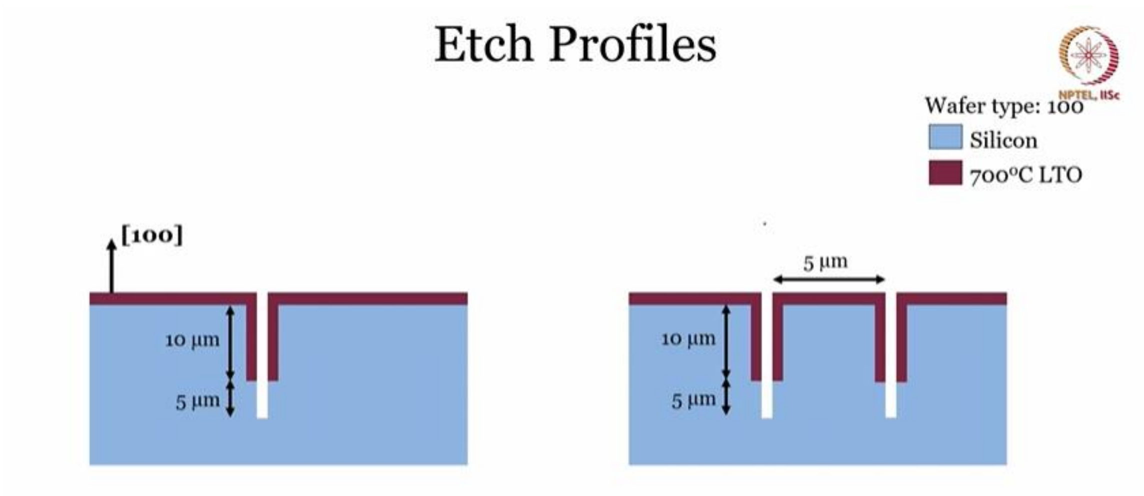
On the right side also, the mask is the same but instead of having a cross section along the edges, I am having a cross section along the diagonal. So, how does it matter? here the length will be $a/\sqrt{2}$, instead of a/2.



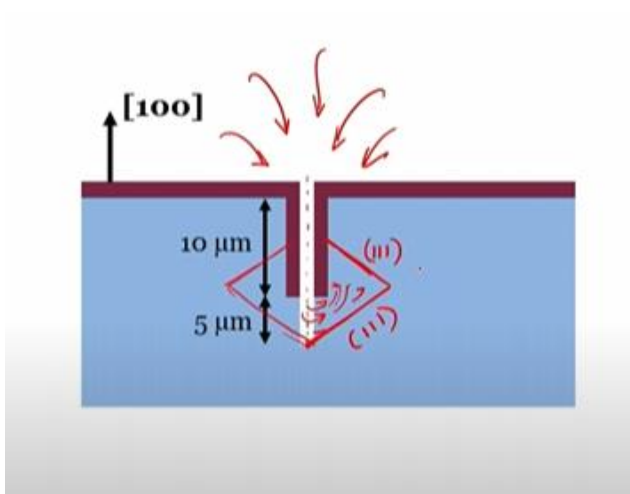
Again, if you carefully observe this cross section, what I am having is actually an angle between two <1 1 0> lines. Previously, I has a plane represented by (111), and here, I have a direction, represented by [110]. So, the angle between 1 1 0 and 1 0 0 we have already calculated is 45 degree. So, we can take a tan of 45 and finally, when we end up with this solution where x turns out to be 0.707.

And if you compare these two sides, we see that the if my edge length if my edge length is a and my mask edge is aligned to let us say 1 1 0, no matter what cross section I am seeing the x upon a, basically the depth to the mask edge length ratio remains the same.

Now, keeping that in mind let us have a quick problem here. It is a little interesting because here we are having something we are not just etching away from the surface, but rather there is a pit.

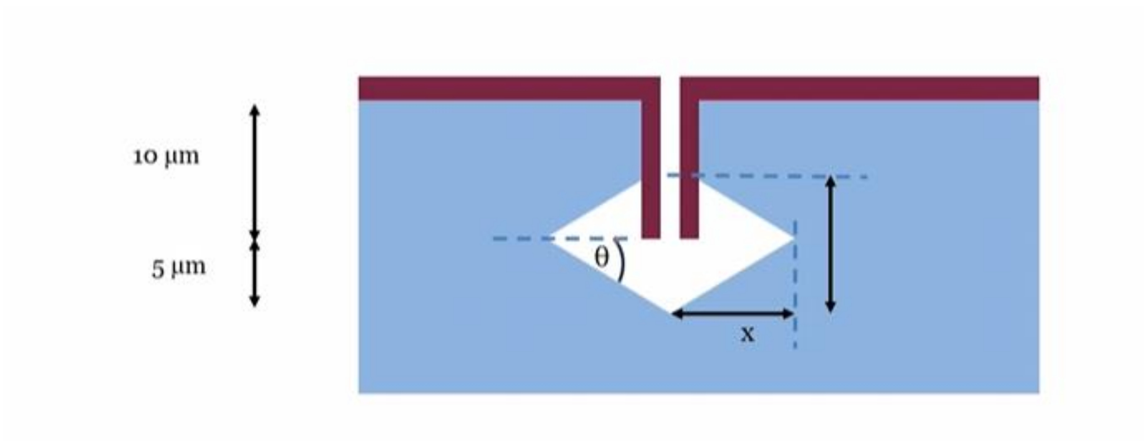


So, let us focus on the figure on the left hand. So, let us say here it is basically a groove and my etchant is coming from the top. So, what will happen is my etchant will ingress from this cavity here and it will start etching on the sides.

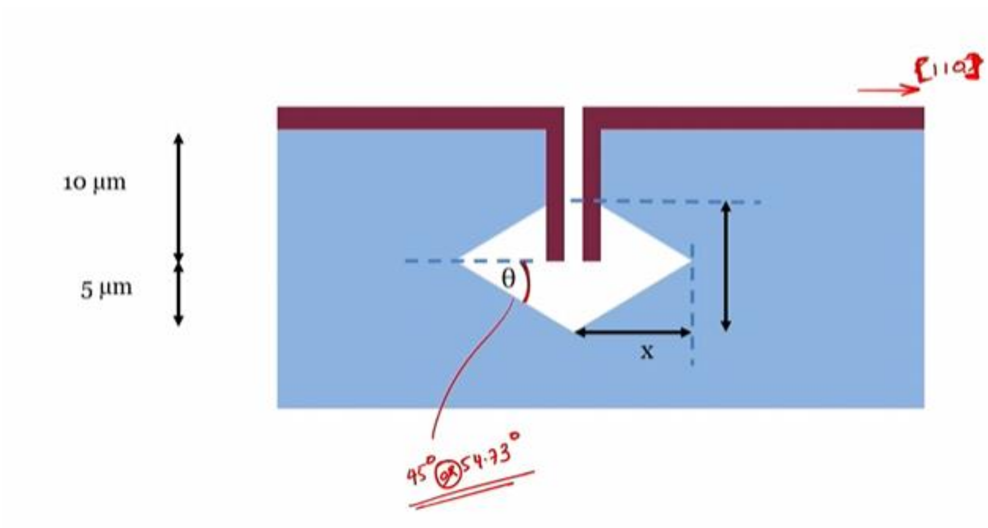


Etching it will stop when it sees a 1 1 1 plane. but it is also going on the top as it sees a 100 plane and it starts etching everywhere. So, it will stop when it sees another 1 1 1 plane. So, basically I will have a cavity on both the sides of the pit

So, I will have this kind of shape which will be confined by 1 1 1 planes. So, if you come here this is the kind of cavity you will get and this angle will be θ.



Depending upon which cross section we are viewing it can be either 45 degree or it can be 54.73 or 54.74 degrees. Now, let us say this cross section what I am viewing this here is 1 1 0 direction.



If this is 1 1 0 , then the angle is 54.74. So, in that case what happens is,

$$\theta = 54.73^\circ$$

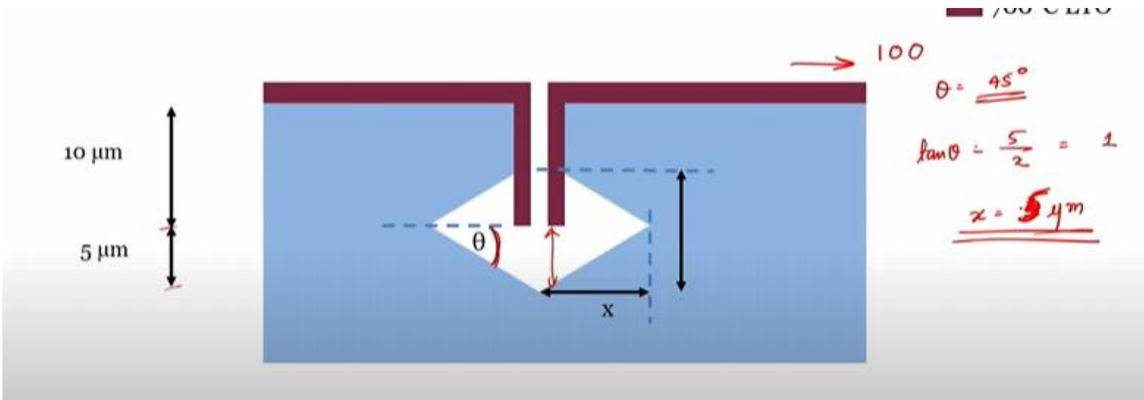
$$\tan\theta = \frac{5}{x} = \sqrt{2}$$

$$x = \frac{5}{\sqrt{2}} = \frac{10\sqrt{2}}{2}$$

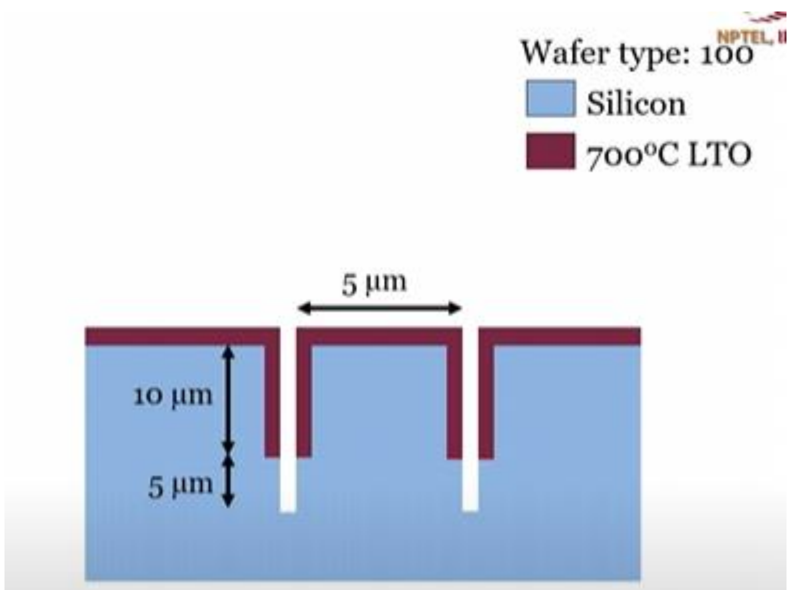
$$= 3.53\,\mu m$$

So, x turns out to be somewhere around 3.53 microns.

Similarly if in the other case let us say this direction was actually 1 0 0, then the angle would be 45 degrees, and after the calculation, x turns out to be 5 microns.



So, depending upon the cross section from which where I am viewing, the cross section can be 5 micron or 3.53 microns. And I would request you to try the other problem what I have on the right side. Try this problem and see what you get in both the cases.



So, that is pretty much everything what I had to talk about and so we will have a quick summary. We started with what is etching, the types of etching, wet, dry, isotropic, anisotropic, what is the criteria for selecting an etchant and why anisotropic wet etching is a little counterintuitive or why it is complicated and how the knowledge of Miller indices and crystal planes can help us in designing very complicated microstructures and what are the mathematics behind them. So, with this we stop here. Thank you.