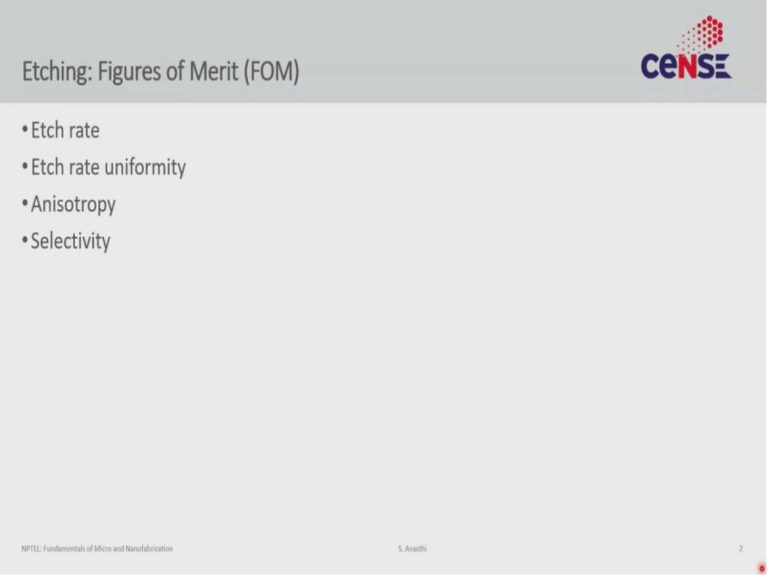
Fundamentals of Micro and Nanofabrication
Prof. Sushobhan Avasthi
Centre for Nano Science and Engineering
Indian Institute of Science, Bengaluru

Lecture – 42
Etching Figures of Merit

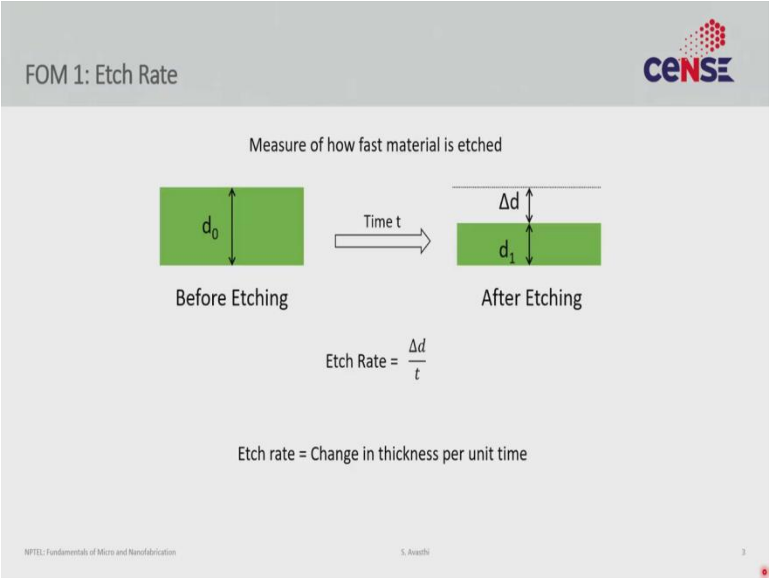
We start a new module on Subtractive Manufacturing, specifically Wet Etching. The first lecture is on Figures of Merit, just as we discussed various jargon and definitions for deposition.

(Refer Slide Time: 00:58)



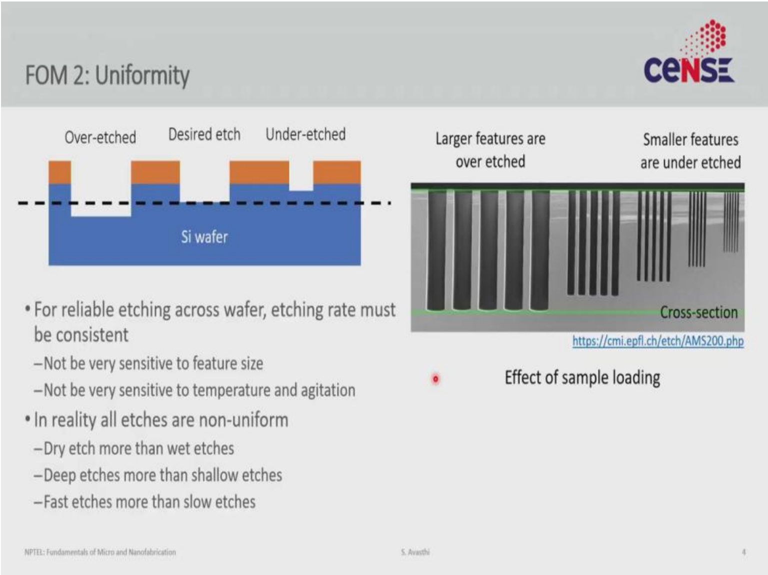
The four figures of merit that we shall discuss in this lecture are etching rate, etch rate uniformity, anisotropy, and selectivity.

(Refer Slide Time: 01:10)



Suppose you have a film of thickness d_o, and you want to etch this film to make it thinner. You would put it in an etchant, dry or wet, and it would eat away the material, making the film thinner. The rate at which the film becomes thinner is the etch rate. If in time t, you lose Δd of this material, then the etch rate is Δd/t. It is, as you can imagine, one of the most fundamental parameters for any etching recipe. However, there are complications that we shall talk about next.

(Refer Slide Time: 01:58)



The etching is not always uniform for several reasons; the etching solution itself may have fundamental issues that prevent it from being uniform. A good example is if the solution produces precipitates randomly on different parts of the wafer. It makes the solution-wafer exposure, and hence, the etch rate nonuniform. Even if those fundamental issues are absent, and the etching solution has ideal chemistry, other things can happen.

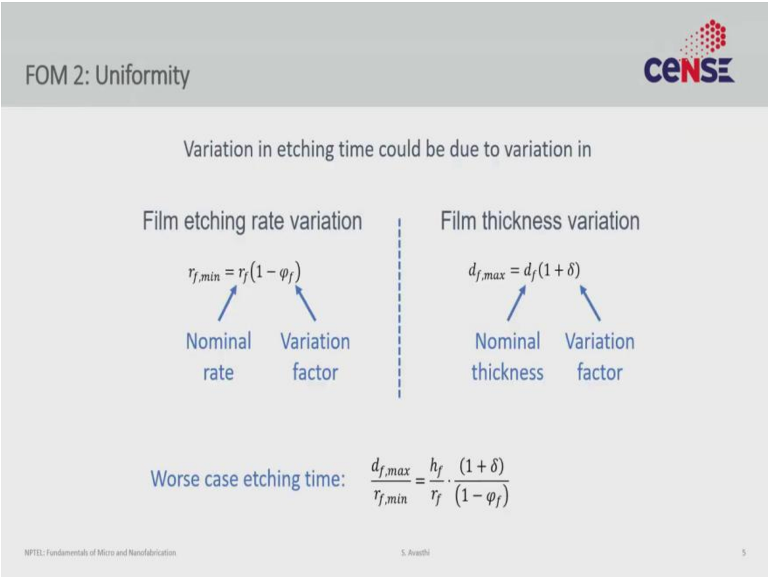
For example, for very tiny features, the etch rate may depend on the size. Let’s take an example of a silicon wafer with three feature sizes in the order of nanometers. The etchant must enter and wet the smaller features to continue etching. It often becomes hard for an etching solution or plasma to get in them, leading to lower etching rates. If all the etch features were of the same dimension, it would not be so much of a problem. You would have a lower etching rate, but at least, it would be consistent across the wafer. In a real mask, you have different devices with different opening areas and patterns. All that heterogeneity means you get different etching rates. A unit process is usually developed for a particular feature size and might work very well for it. However, for smaller feature sizes, you might get a lower etching rate. There is also an effect of sample loading, which we shall deal with when we talk about the etching solutions, especially in dry etch.

On the right, you have an SEM image of anisotropic dry etching of very high aspect ratio features. Depending upon the opening area of the hole, for the same etch time, you get different etch depths. The larger holes etch deeper, in this case, because of mass transport. In etching, both the etchant must go in, and the byproducts must go out. It is harder for the narrow or small opening area features than the broader features.

To get uniformity, you don’t want extreme sensitivity to temperature or agitation. A lot of etching solutions are exothermic or endothermic. Some of them need external heating. So, you can never keep the temperature strictly uniform. The etching solutions or recipes that are extremely sensitive to temperature require very high uniformity and are often not ideal. You have the same thing with agitation. During CVD, we talked about diffusion through a boundary layer - the precursor in, and the byproducts out. In etching, agitating the solution can help the etchant to get in and the byproducts to get out. It improves the etch rate. However, agitation, by definition, is nonuniform, and that affects your etching uniformity. You have to optimize the chemistry such that the etching solution should not be very aggressive or too passive.

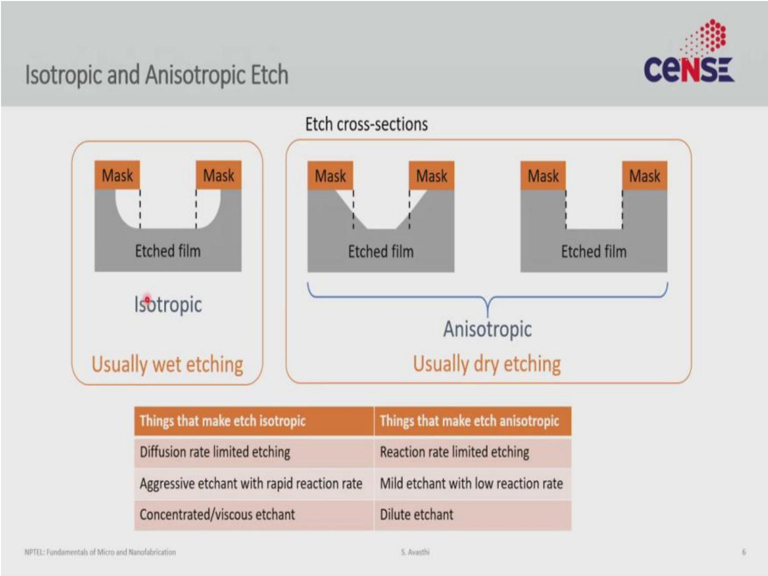
In reality, all etchants have some level of non-uniformity. The trick is to precisely characterize the etch rates so that an engineer can design around it. In general, dry etch is a little more nonuniform than a wet etching, and deep (and narrow) etch is more nonuniform than shallow etch. Typically, fast etch is much more nonuniform than slow, as it comes to the ability to control; something that happens very fast is hard to control, as compared to something that happens slower.

(Refer Slide Time: 08:07)



When you design an etching recipe, you typically start with nominal etch-time. Suppose you want to etch a film of 100 nm, and the process engineer gives you an etching solution that etches at 10 nm/s, you need to put it in the etchant for 10 s. But that is just a nominal etch-rate. The etch-rate, as well as the film thickness, is nonuniform. You have to account for both to calculate the worst-case etch-time or the time that you must do the etch to make sure that all the features reach the required depth. Let the nominal etch-rate be r_f, with a nonuniformity φ_f. The minimum etch-rate would be $r_f(1-\varphi_f)$. Nominally, you have a film about d_f thick. Due to nonuniformity, the maximum thickness you get is $d_f(1+\delta)$, where δ is the variation of the film thickness. The worst-case or the maximum etch-time $\frac{d_{f,max}}{r_{f,min}} = \frac{d_f}{r_f} * \frac{(1+\delta)}{(1-\phi_f)}$ is the time required to etch the thickest part of the film at the lowest rate. Be sensitive to the variations. When the deposition is the first step, you only have to worry about the deposition uniformity. By the time you come to etching, you have to start worrying about the uniformity of all the preceding processes to ensure a good yield.

(Refer Slide Time: 11:21)



Here are some illustrations of isotropic and anisotropic etches. Let's start with the simplest - the isotropic etch. You can see the cross-section of the films along with the masks. We have already discussed masking and lithography. The dotted line represents the design opening. However, the feature that you get is slightly wider. You want to etch the film vertically to the depth d. Isotropic etchant etches equally in all the directions - vertically as well as laterally (on the left and right side of the opening). I have shown here the extreme case of completely isotropic etch. So the depth and the additional lateral width are the same. However, it is an exaggeration that does not always happen.

You get a slightly wider opening than your design. It becomes problematic for high aspect ratio features (narrow and deep etch). If the width becomes comparable in size to the etch depth, you have to consider the impact of isotropic etch. Often you can characterize the lateral etch and then compensate for it in your design itself.

The other case is the anisotropic etch, and an extreme example is in the figure on the right. You have a pattern on your silicon film, and these dotted lines represent the intended opening. When you etch using an anisotropic etchant, the sidewall is vertical. There is no etching in the lateral direction. It is a 100 % anisotropic etch. Anisotropic (not isotropic) means it is not equal everywhere.

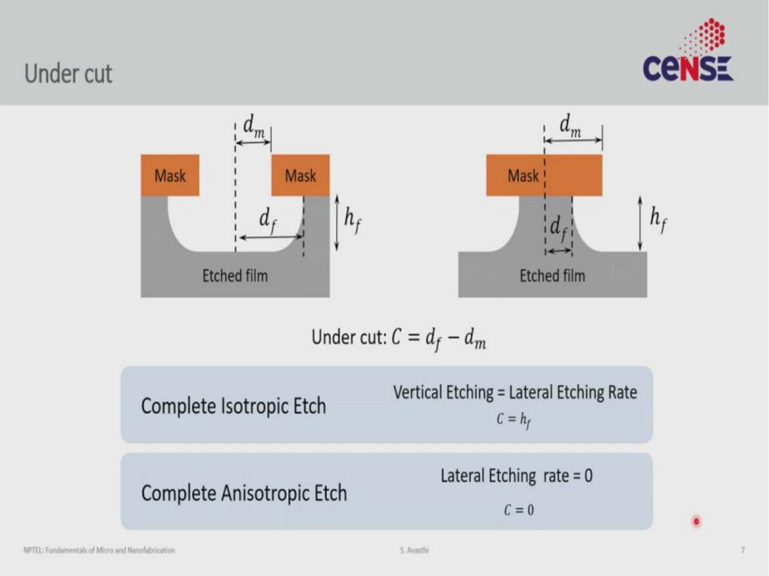
The reality is somewhere in the middle. The etchants often have some anisotropy. You do not get 90^o sidewalls, or exact spherical or cylindrical sidewalls either, but something in the middle. You call the etching anisotropic if the cross-section looks like the figure on the right, and isotropic if it looks like the figure on the left. In general, wet etching, where you use liquid etchants, tends to be isotropic. Dry etching, where you use plasma, tends to be anisotropic. Of course, there are exceptions. You can get anisotropic wet etching and isotropic dry etching recipes, which we shall discuss later.

Remember the lectures on CVD. We had two rate-limiting cases. The precursor diffused through a boundary layer to the surface and reacted. We talked about how these fluxes, the diffusion flux, and the reaction flux have to be in balance. It led to two different deposition regimes, where the rate could either be diffusion (mass transport) limited or surface reaction-limited. The etching is essentially a deposition process in reverse. So the same basics are applicable. The etch-rate has the same bottlenecks - the diffusion rate through the boundary layer of the etching solution or the surface reaction rate. Depending upon which of these is the limiting factor, the etch can be isotropic or anisotropic.

Typically diffusion-limited etchings tend to be isotropic, and this is not hard to understand because diffusion is direction agnostic. Etchants diffuse vertically and laterally at the same rate, which would give you an isotropic etch. However, if the etch rate is surface reaction limited, it can have a directional dependence. Different facets of the crystal may etch at different rates as they have different surface energies. It makes the etching anisotropic.

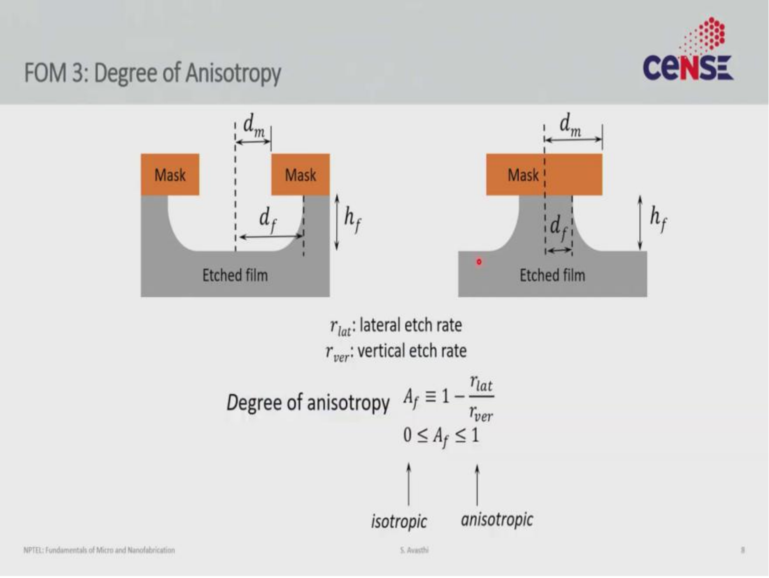
Very aggressive chemicals that have very rapid reaction rates tend to etch isotropically. As the surface reaction rate is high, diffusion (the slower step) limits the etch-rate and makes it isotropic. Mild etchants have a low reaction rate, which becomes the bottleneck. So, they can be anisotropic. For concentrated and viscous etchants, diffusion is very slow. Once again, you are diffusion-limited, and that makes the etching isotropic. For dilute etchants, the diffusion rate is fast. They tend to be anisotropic. These are just thumb rules, and good to start the design. Details are complicated.

(Refer Slide Time: 18:11)



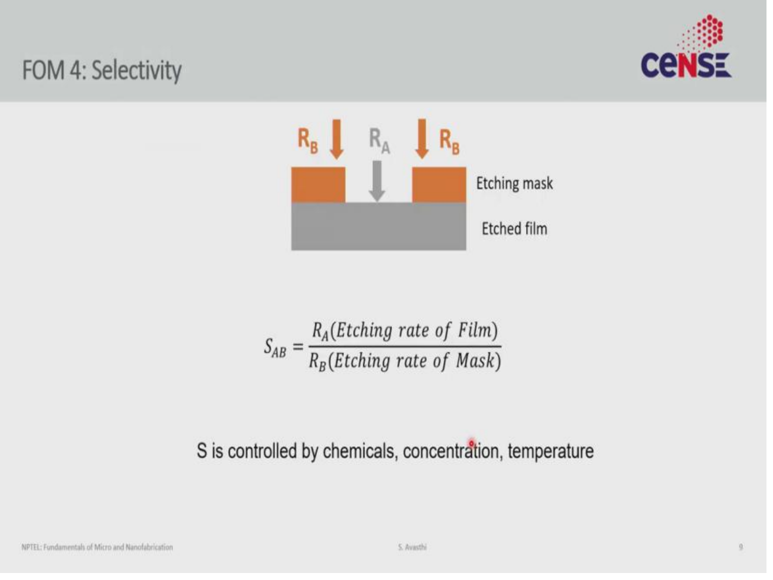
Isotropy of the etching leads to undercutting. For a mask with an opening of $2*d_m$, you get a hole of width $2*d_f > 2*d_m$ because of isotropic etch. The etchant will not just etch vertically, but also laterally. The undercut (C) is the difference between these two parameters, $C = d_f - d_m$. For isotropic etch, the undercut is large. For very anisotropic etch, it is 0. For all practical cases, the undercut is somewhere in the middle. The effect of the undercut depends on the pattern. Here, C increases the size of the hole. However, if you are trying to etch a pillar, the undercut would decrease its diameter. For the pillar $d_f < d_m$ because of the lateral etching.

(Refer Slide Time: 20:07)



The third figure of merit often reported for etching solutions is the degree of anisotropy. It is related to undercut. It tells the difference between the lateral (r_{lat}) and the vertical (r_{ver}) etch-rate. $A_f = 1 - \frac{r_{lat}}{r_{ver}}$. If the solution is isotropic, $r_{lat} = r_{ver}$, and the degree of anisotropy Af = 0. If, in the other extreme, $r_{lat} = 0$, $A_f = 1$, indicating completely anisotropic etch. In the practical cases, $0 < A_f < 1$. A_f tells how anisotropic the etch is.

(Refer Slide Time: 21:12)



The fourth and a significant parameter of an etching recipe is selectivity. In general, you rarely etch a blanket film, but often want to transfer the mask pattern to the substrate. Suppose you are etching this gray film with some masking pattern (the orange photoresist). When you etch the film, the etchant can also etch the mask a little. The degree at which it the etchant etches the mask versus the film is called selectivity. A is the film you want to pattern, and B is the mask.

Selectivity $S_{AB} = \frac{R_A}{R_B}$. R_A and R_B are the etch rates of the film and the mask, respectively. If $R_B = 0$, the selectivity is infinity, meaning that you are not etching the masking layer at all. You are only etching the film, which is the ideal case. In general, you always etch the masking layer, although at a slower rate. So, the selectivity is finite. If S = 1, the etching rate of the mask and the film are equal. You may think that would be worthless, but it is not. It means that the maximum etching depth that you can achieve equals the mask thickness. If your mask thickness is 1 µm, and S = 1, the maximum you can drill is 1 µm.

If, however, S = 100, for a 1 µm thick mask, you can etch a 100 µm. A higher selectivity is desirable. In some extreme cases of $S < 1$, you need a much thicker masking layer to get a certain etching depth. It often is the case for materials that are very hard to etch, for example, some oxides, some very stable or noble metals.

The selectivity depends on the etchant's chemistry with the mask and the film. An acid would attack a metal very fast, but not a polymer. So, with an acidic etchant, a polymer may have very high selectivity against the metal. However, the base can attack both, so the selectivity would not be so good. S also depends on concentration and temperature. Dilute solutions tend to be a little more selective. At low temperatures, you get better selectivity. At high temperature, virtually everything starts etching, so you get lower S. Again, these are just thumb rules. You always need to look at the details.

In the next lecture, we will get into the basics of etching and look at some actual recipes.