Fundamentals of Micro and Nanofabrication
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Lecture – 37
Lithography process technology glossary

In this lecture, we are going to look at some of the important lithography terms that we use in processing and qualification as well. And, also we will look at how to improve the quality and what are all the parameters that affect the quality of printing on the wafer.

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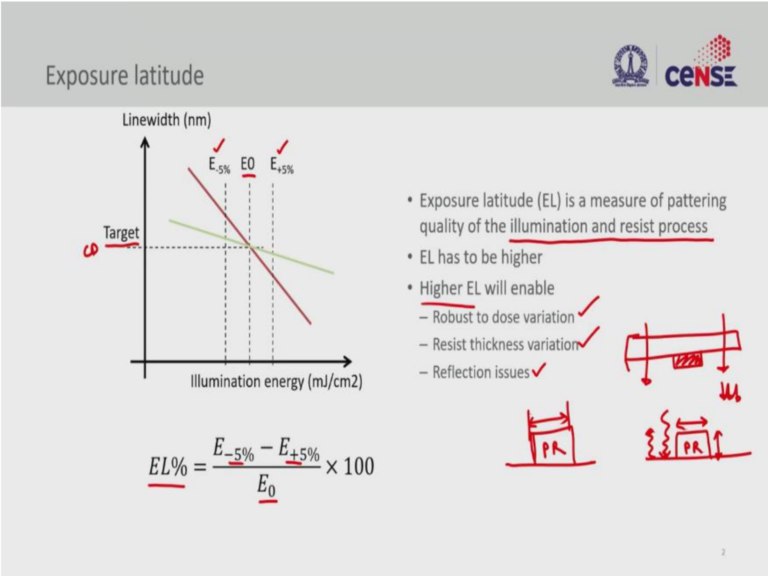

So, the first term is exposure latitude. So, what do we mean by exposure latitude? Exposure latitude is a measure of patterning quality of the illumination and resist process put together. So, it qualifies both illumination and resist process together. Say, we are measuring the line width of your photoresist after patterning. So, we have developed and we have gotten this photoresist pattern and then we are measuring the dimension of this pattern and then we are qualifying how good the exposure stability is.

So, just to give you an example on the left side you see a graph that shows two lines; one is green the other one is brown. So, let us look at the green line and then the x-axis is the illuminating dose. When I increase the dose, the line width reduces. So, in this case just to you know recall, you have an opaque region and then you have illuminating region on the side. In a positive photoresist, whatever you illuminate will be washed away and the remaining resist remains. So, when I increase the dose, the line width is going to shrink. And, then there is another process (brown line in the graph) that has a steeper slope.

So, now, I have a certain target line width, you call the critical dimension and then I want to see how much is my variation in my critical dimension if I change my exposure; in this case, ±5 %. So, E_o is the target dose or optimal dose that will give me the actual target width.

And, then I would like to see if I change my exposure dose by ±5 % (i.e., $E_{\pm 5\%}$) how my critical dimension is going to vary. So, this is very natural to expect because when you are illuminating it is very hard to expect that your illumination will always be constant. But, there could be some fluctuation in the illuminating dose. So, that is one cost and the other cost could be your wafer itself. So, if the wafer is not flat, and if your focus is not proper you will also see some change in the energy that reaches the surface.

So, you want to understand how changes in the exposure dose can change my critical dimension. This can be characterized by exposure latitude percentage.

$$EL\% = \frac{E_{-5\%} - E_{+5\%}}{E_o} * 100$$

Exposure latitude gives us an idea of how much change in the exposure dose and how much change we obtain in the critical dimension. So, this actually enables us to qualify the robustness of the process to a dose variation and thickness variation as well, because your dose changes as a function of thickness of photoresist. If the photoresist is thick you need more energy and if the photoresist is thin you need less energy. Practically, you will always have some thickness variation across the wafer when you coat the photoresist. So, you have to know how robust your dose variation is to your thickness of photoresist.

As we discussed in the earlier lectures, there are reflection issues as well, where when the light comes down and when hits it so, there will be also some reflection. So, if the reflected light also exposes the photoresist that is something that we should also take into account and this exposure latitude will help you to understand how well you can control it. You always want higher exposure latitude. So, you want the latitude to be larger, so that your process is very robust.

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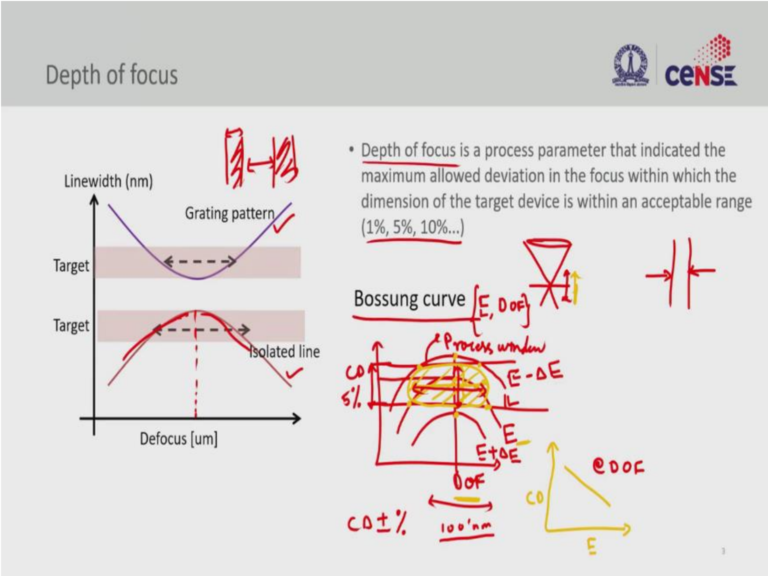

And, then the next thing is about depth of focus. We discussed about depth of focus in our imaging lectures: how does the focus affects the image and what is the origin of this depth of focus were discussed. In this case let us see what happens if we change the depth of focus. Consider an isolated line with a certain critical dimension.

And, now I am changing the focus. So, this change in focus could be coming from your wafer location. So, if it is not at the optimal location I am going to go up and down. So, this is how your rays are going to look and at the optimal focus you get the best image. This is like the picture that we take with your camera.

So, I am going to move this focal plane up and down. So, the critical dimension is also changing because of non-optimal focus and this is what we capture in the exposure dose and variation picture. So, the depth of focus is measured by varying the focus onto the wafer and measuring that target CD.

So, if I change the focus obviously, there is a change in the time engine. So, I get an isolated line (IL) for a certain energy E and this is your CD for a certain **depth of focus**. So, obviously, there is a target that I reach, but then if I change my depth of focus my CD changes, but then my dose will also vary which we discussed earlier in the exposure latitude.

So, what happens if I change my dose? So, if I reduce my dose $E-\Delta E$, your CD is going to increase. If I increase the dose to $E+\Delta E$, CD will reduce. So, now if you take this best depth of focus all these points what you actually get is your exposure latitude image that we discussed earlier. So, now, by changing the depth of focus I get this group of plots. So, this variation in both exposure dose and depth of focus is called Bossung curve. So, you change both energy and also depth of focus and this is what we call dose exposure focus or exposure matrix and this is called Bossung curve and you get this kind of set of individual plots.

So, here we are looking at the process window, i.e., an acceptable range of dimension for the designer. So, when you design something you design for a certain dimension and then you give a certain percentage variation. When you design a device or a circuit you say see if my critical dimension variation is within 5 % or within 1 % my device would work as desired or will still yield what I actually intend to do.

So, you want to look at what is the window of exposure dose and your depth of focus within which you will get this desired variation. So, let us say ±5 % of CD is within this window, then draw lines from ±5 % of CD and then that line will intersect within all these curves and provide some interesting points. So, within designer specification and within this particular window, I am within my required specification. So, I do not have to worry about the exact depth of focus or exact exposure dose. My dose can vary within this range and my depth of focus or the focal point can vary within this region and this is what makes lithography, the projection lithography very robust.

You see pretty large windows in the order of a few tens or hundreds of nm. The window of exposure dose can be 5 to 10 % variation which in commercial systems are tight, but your depth of focus is controlled by your wafer flatness and so on. So, you create this kind of a focus exposure matrix in other words Bossung curve, so that you can qualify your process window and this becomes a very essential part in lithography process optimization.

This only applies to projection lithography system; in contact lithography system you do not have this problem of depth of focus. The reason for that is both your mask and your wafer are in contact. There is a no issue of depth of focus or focal point. The nature of the curve will vary. So, here we saw a downward looking curve and on the top for the grating you look at upward looking graph. So, this depends on whether you are looking at a line or a trench.

So, if it is a dense pattern if you are looking at this trench or whether you are looking at this line based on what you are measuring. Your nature of the curve can be different, but nonetheless the investigation to look at the process window is going to be the same.

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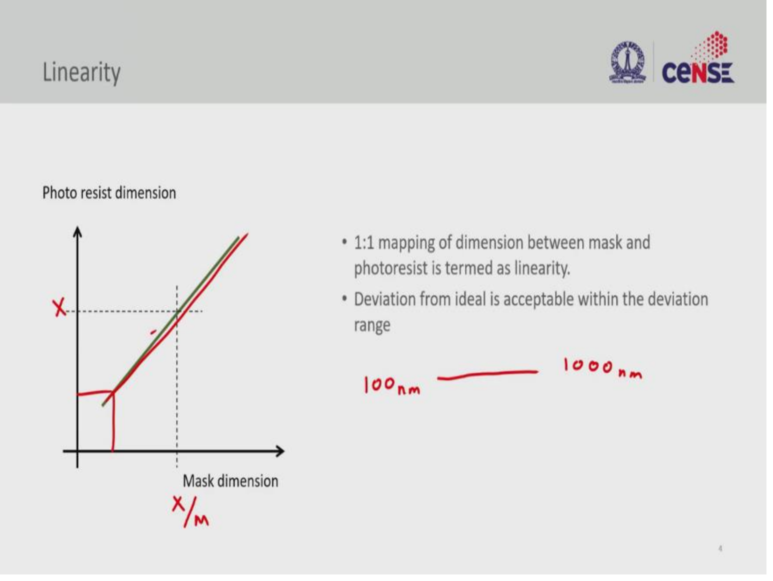

And, the next thing is the linearity. So, what is linearity? So, we want to have one to one mapping of the dimension between mask and photoresis. So, if the mask dimension is you know some ‘x’. Of course, this is taking into account the magnification factor and on the mask as well the wafer you want to have the same dimension. So, this is what we call linearity.

So, you could have varying dimension on the mask and on your design. So, one structure might be 100 nm and other could be 1000 nm. So, you can go from 100 nm to a micron, but you want all these structure to yield to accuracy, so that your circuits are performing the way you want to.

So, how do we ensure that all these devices yield? So, in order to that, you want to look at the linearity of this processor. So, normally this is done through metrology. So, you will take different dimension and see what I had on the mask and what do I get on the photoresistor. So, if you do this mapping, I want it to be very linear. So, the linearity qualifies the process is good for varying dimension.

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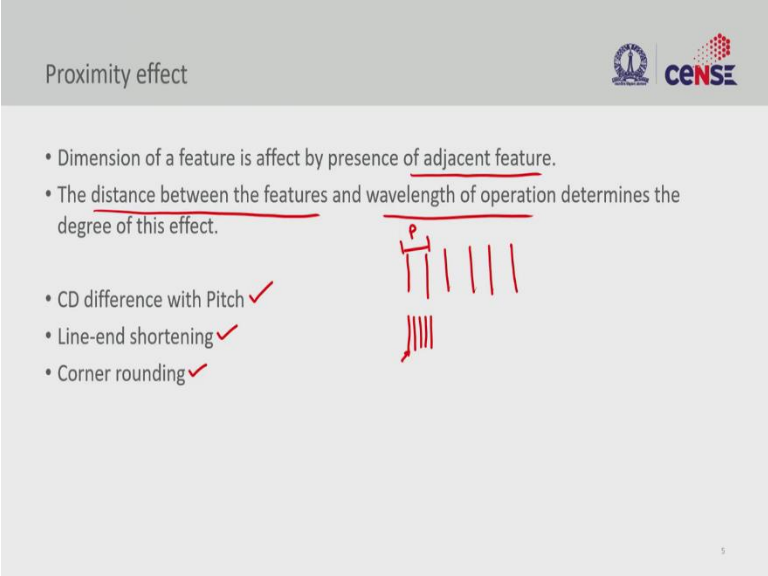

And, the next thing is proximity effect. Proximity effect is an undesirable effect in this whole imaging system. So, the dimension of the feature is affected by presence of features adjacent to your desired feature. So, if the dimension of my desired devices or feature is affected by the neighbouring feature, we call it as proximity effect. And, this depends on the distance between the feature and the wavelength of the light. So, these are all the things that determines the degree of this proximity effect.

And, this proximity effect could bring in CD variation with respect to pitch. So, what is pitch here? So, if I have line space structure, the distance between two consecutive lines or space is what we call pitch. So, as I reduce the pitch my neighbouring device is coming closer or neighbouring feature is coming close to my line . They are closely spaced and hence, this will have an effect on the trench width or the line width. Line-end shortening (we will see that in a bit), is also an undesirable factor because of proximity. Corner rounding is also an issue because of proximity. Let us look at these things a little bit more carefully.

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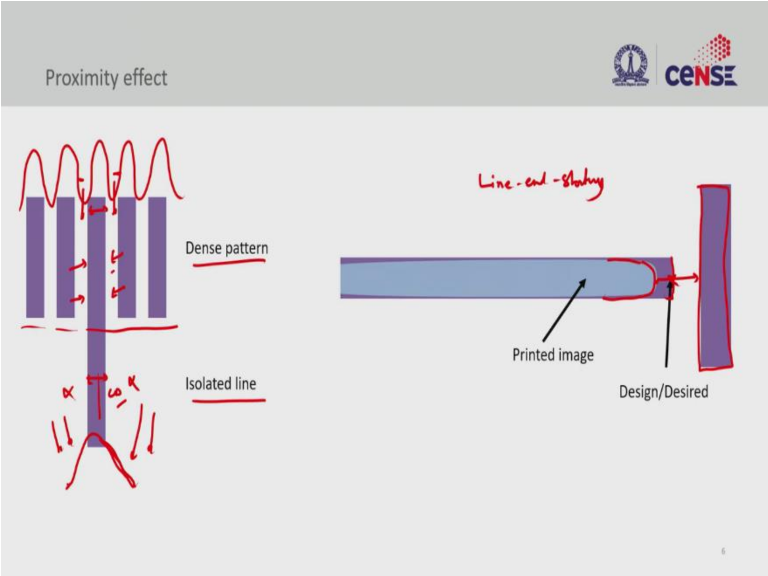

So, let us look at how these proximity effect affects the structures. So, consider a structure having a dense and isolated feature. All the lines have the same CD, but the only difference is the environment change. So, on the top we have dense feature. So, you have other features coming close to the line of interest, but then the bottom side you can see it is free. So, there is no structures coming close to the device.

So, when we print this, we will find out that the dimension of the central line is not uniform and it is going to have a CD variation. So, the critical dimension or the line width is going to be different. So, let us understand how this is going to work. So, we have a dense feature on the top. So the amount of light that is going to come through the top end is going to be very less and also it is going to be affected by these two features.

It will be better to understand by looking at the aerial image. So, on the surface of the photoresist you will find an image like this. So, this is what the intensity pattern is going to look like. So, as you can see here you are very close to this edge. So, the presence of the two lines right adjacent to the centre line is actually pulling the power down here; that means, your patterns will be slightly narrower in feature, but then if you take the isolated line you have broader feature.

So, when I look at this whole structure on the top end your line width is going to be narrow, and at the bottom side your line width is going to be broad. So, this is proximity effect. So, there are multiple ways to address this proximity effect such as adding assist features and so on, which we will see that in a bit.

So, now we will look at what is the effect of proximity first and on the right side we have something called line-end shortening. So, in this case I have a line with a perpendicular feature coming close to this line with a certain distance. So, when I print this image what I will get is a shortened line. So, instead of having your edge close to this line, edge will be much smaller. So, the reason for that again is that you do not have sufficient distance between these two lines and inefficiency in getting light through this system makes this line shortened.

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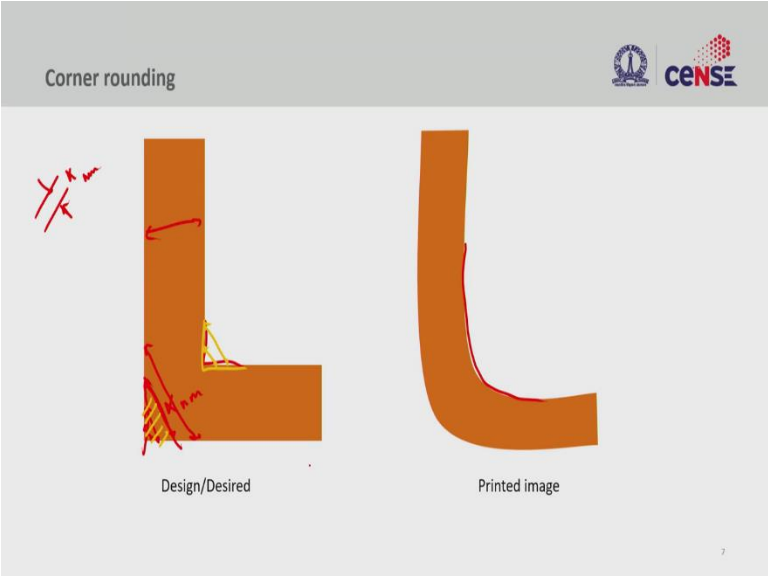

And, then the next thing is about corner rounding. So, on the left side you see the mask pattern. This is what a designer wants to write with very sharp corners. But then when you print it you see a rounded edge (image on the right side of the slide). So, the reason for this is a resolution basically. So, let us understand what the resolution limit is.

So, we say resolution limit is how small a feature can be printed. So, consider a certain critical dimension and let us have a look at this corners a bit carefully. So, as I move closer and closer to the edge, the dimension reduces and at this point (corner) the dimension will be zero nm or so. So, if my resolution is let us say a certain ‘x’ nm I will be able to image only to that ‘x’ nm. So, below this I would not be able to reproduce that image at all. So, whatever features I have below ‘x’ nm I would not be able to reproduce. The same thing applies to this edge also and you would not be able to reproduce that corners.

And, these sharp corners have got high frequency. The sharp corners can be only reproduced if you have large number of coefficients i.e., In the Fourier series you need large number of coefficients to reproduce this and in other words you need more number of diffraction orders in order to reproduce the sharp corners. This is again the resolution limit.

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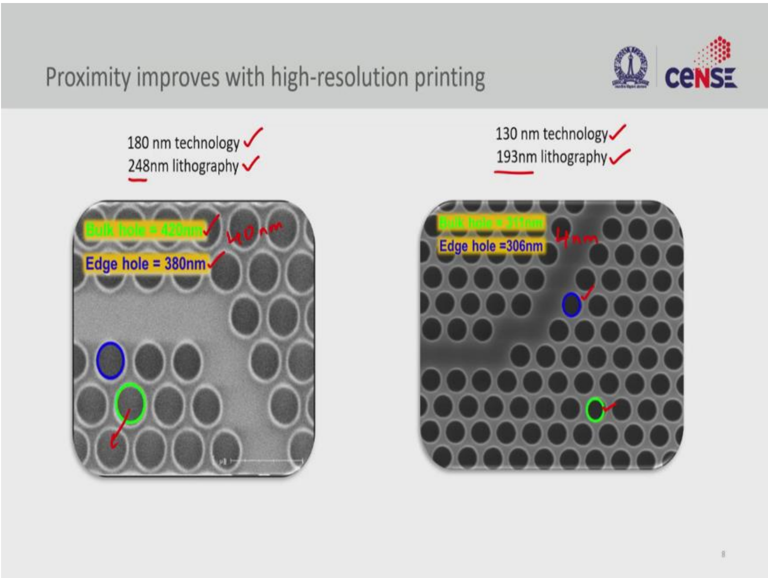

And, this is an example of how to improve your resolution. And, proximity effect is a classic example of resolution enhancement. On the left side, you see 180 nm technology and 248 nm illuminating optics. Say, we are illuminating the same object and the bulk holes. As a result, the holes that are inside got a hole diameter of 420 nm and the edge holes got only 380 nm. This is a classic proximity effect, the edge effects.

But, then I am imaging the same structure by using 193 nm illuminating optics and lasers and using 130 nm node technology. With this process, the difference is only 4 nm, whereas in the previous case it is about 40 nm. So, look at the reduction in the non-uniformity when the optics and technology node is changed. So, this is the reason why going to higher resolution or reducing the wavelength will help us in tackling this proximity problem.

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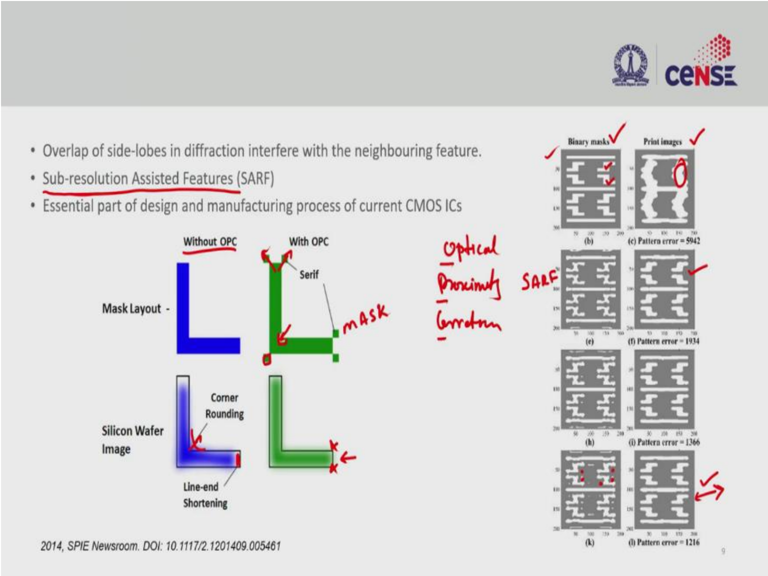

And, the other thing to circumvent the proximity issue is by using assist features. So, we saw this L shape earlier with some rounded corner. So, this is a simulation image on the left side without OPC (Optical Proximity Correction). So, if you do not do any optical proximity correction you get two things; one is line-end shortening, the other thing is the corner rounding.

So, how do we handle this? The way to handle this is by adding sub-resolution assist features. And, here since lines are getting shortened we add the assist features to extend the line. These kind of sub-resolution assist features are added in order to pull the light out.

Similarly, in this corner you are getting a structure outside your area of interest. So, what you do is you push it in; that means, we remove that particular area (where there is no structure in that area) and then we add a structure outside to get an optimal image.

So, this is an assist feature, but we call it a sub-resolution. The reason for that is it is present in the mask, this is at mask level. It is present in the mask, but not present in the image. So, in the image if we do not want anything in the mask to be reproduced on the image you want to make it sub resolution that mean it is below the resolution of the imaging optics. On the right side of the slide is a very good demonstration of how to convert a simple binary pattern by using the assist features and then reproduce what you want. As you can see here this is a complex structure to enhance the proximity effect.

So, whatever you have printed is completely different from what you want. Instead of getting two isolated features here what you get is a complete blob. But then at the mask level you start adding sub-resolution assist features to get a reasonable reproduction.

But now I am going to take this to a different level by profiling the optics. You see the assist features are all over the place and then when I do that the image is very close to what I wanted from the binary image that I have. So, this is how you create nearly perfect reproduction of the image by using sub-resolution assist features (SARF). SARF is very difficult to do experimentally because each time you cannot make new masks for all the assist features. So, this is all computationally done and it is called computational lithography where we image this using computational tools and then we feed back the information to the mask design, so that we can get a reasonably good reproduction of this image.

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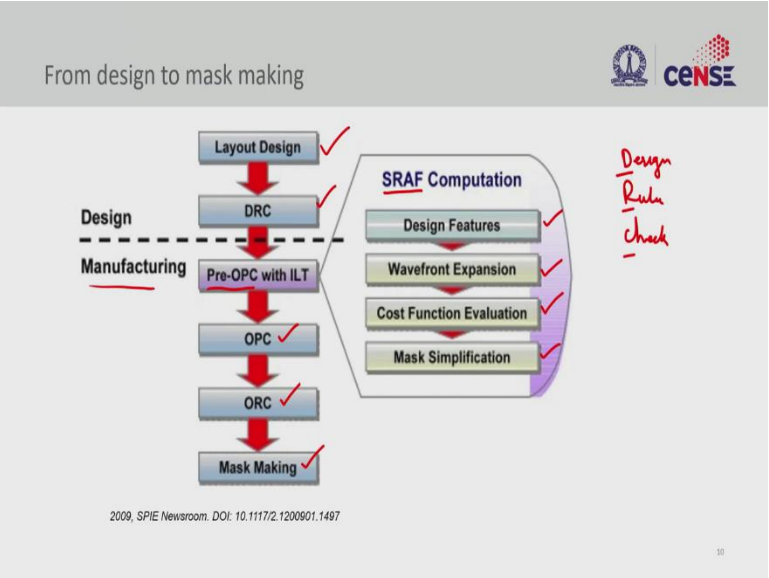

And, this is a process flow to reproduce that mask. So, you start with a layout that is coming from your design and then you do Design Rule Check (DRC). DRC is to check if all the design rules are followed or not. For instance, if the lithography limit is only 50 nm and then in your layout/circuit, if you are asking for 50 nm it is a violation because it cannot be reproduced.

So, this DRC will make sure that you know whatever you design can be reproduced in your wafer. So, that is the first step and once it clears that design rule check, when it goes for manufacturing, we do a pre-OPC (OPC-optical proximity correction). So, first we image it and then see whether we need to do add some the sub-resolution assist features or not.

So, if it is needed we add this, we do a waveform expansion, this is all done using the optics simulation and then we also look at how much assist feature need to be added because that adds cost to the system and then we do some simplification of this assist features because you may not need all the features because when you put it through a wafer from wave front expanded that algorithm is going to add possibly in order to make the image perfect. So, you do smoothening followed by proximity correction and an optical rule check. This is done after adding all these assist features. And then we proceed to mask making. So, these are all the steps involved even before the mask making.

So, this summarizes the process flow in mask making and that brings us to the end of this lecture on the different masks terms that we use to qualify the process and also finally, looked at how to increase the resolution or avoid a proximity effect in this lithography system. So, with this we have a very detailed understanding of the mask technology, important terms that is used in mask processing and litho processing. Now we need to look at how do we increase the resolution of the system.

So, one way to increase the resolution is by adding assist features to avoid the proximity effect. But it involves more adjustment to be accommodated to reproduce the image. For instance, you have 100 nm lines and then in the next technology node you want to reduce that dimension to 50 nm. So, how do you do that? So, what are all the ways to achieve a better resolution with lithography is going to be discussed in the follow up lecture.