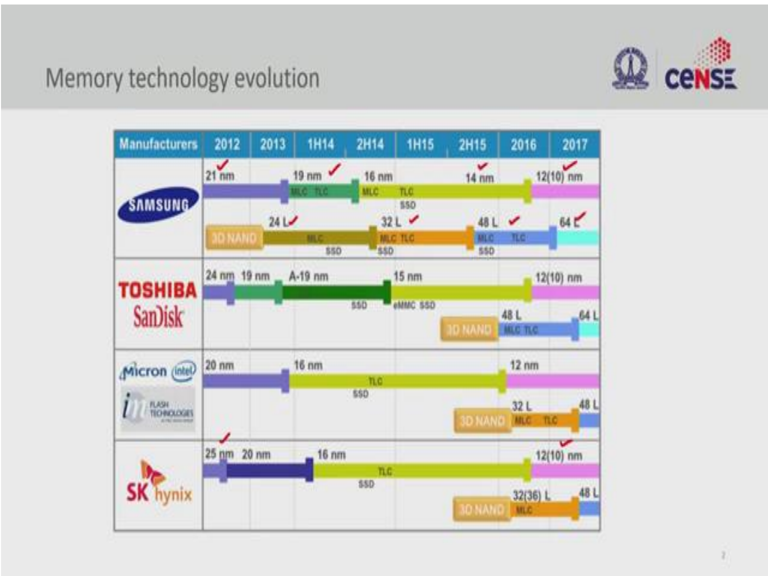
Fundamentals of Micro and Nanofabrication
Prof. Shankar Kumar Selvaraja
Centre for Nano Science and Engineering
Indian Institute of Science, Bengaluru

Lecture – 38
Optical Lithography: Resolution enhancement

So, in this lecture we are going to explore the resolution enhancement techniques in optical lithography. So, resolution enhancement technique is the forefront of current optical lithography technology. So, the reason for that is consistently we have been trying to reduce the feature dimension by advancement in various system improvements not just the system, but also process. But you are actually now reaching the limits of the improvements that one can bring in so, in some of the cases really fundamental physical limits.

So, a resolution enhancement technique how it improves the resolution and what are all the areas we are attacking in order to improve the resolution is going to be the topic in this lecture. So, let us go back and look at what are all the primary contributors or in specific terms, where are the places we could make changes so that could bring in a resolution enhancement.

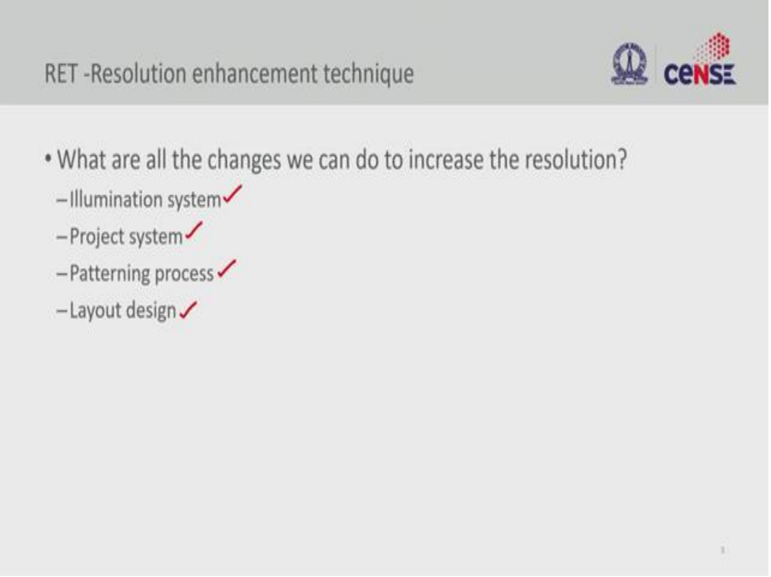
(Refer Slide Time: 01:54)



So, this is a simple timeline that was captured to showcase, how the technology in particular memory technology has evolved over time. So, there are different manufacturers commercial manufacturers and you look at the technology, they use in order to deliver the kind of a memory densities that we are looking at. So, if you look at year after year, you see improvement reduction in the critical dimension. So, this is the gate lengths that they use. So, irrespective of the manufacturer, you have to reduce the size and when you reduce the size, you increase the number of transistors and you have to also increase the number of layers required in order to achieve those connections and so on.

So, in this case 3D a NAND technology that requires large number of interconnect layers. So, the bottom line is, it is evolving. So, we have gone from 20 nm nodes to now we are close to a 10 nm and probably going sub 10 nm in coming years, but then how are we achieving all these enhancements.

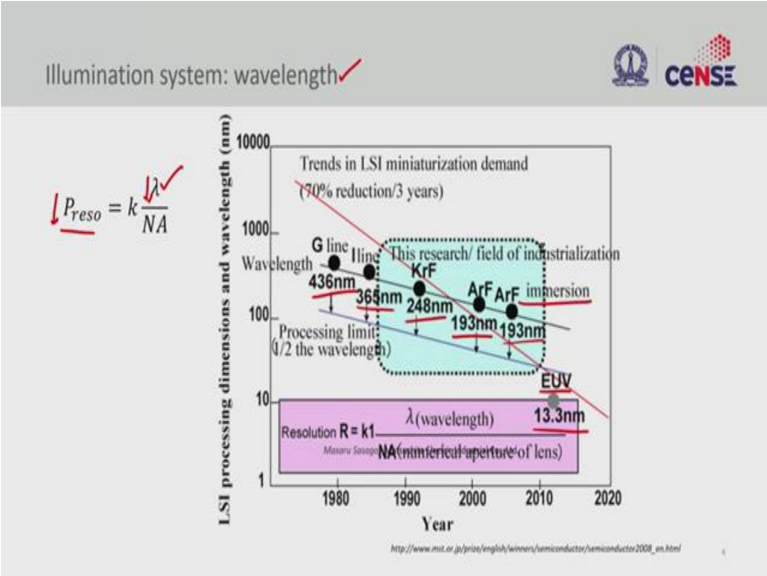
(Refer Slide Time: 03:20)



So, let us look at it objectively. So, the places where you could make difference in resolution enhancement is the illumination system itself, the light source and the illuminating optics. So, whether we can make changes is projection system, that is illuminating and then you are capturing those scattered light from the mask.

And then the next thing is processing technology. So, processing meaning the resist that we use and then how we process the resist and so, on whether we can do something there. And finally, the layout design itself. Can we do something to the design that will make some changes. So, these are all the places where you could make an improvement in a resolution.

(Refer Slide Time: 04:21)



Let us look at one by one. The first thing is the illumination system. Primarily looking at the light source in this case wavelength. So, over the years we know that we have been reducing the size of the transistors. And this image captures, how we are achieving this by reducing the wavelength. So, we started with some UV illumination.

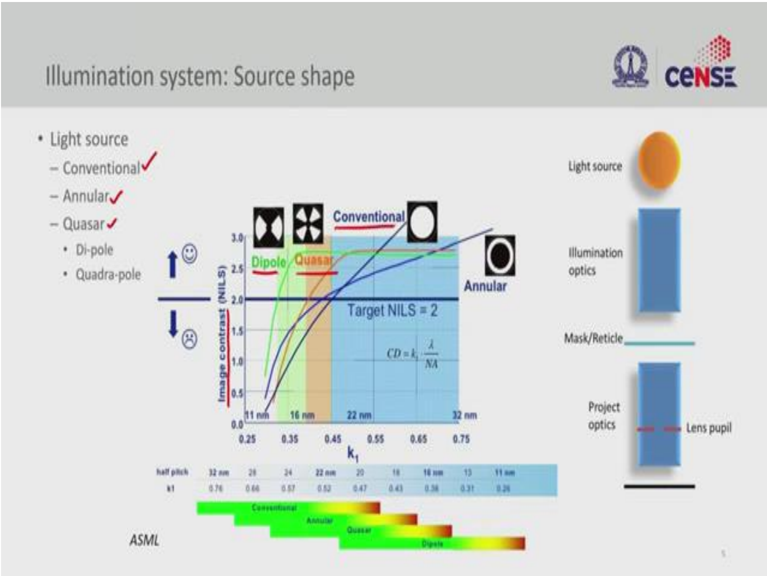
So, this G line and I line if you remember from the mercury vapour lamp, we were able to filter this and use this for micron scale technology. And then we used deep UV 248 nm, this is all now in the laser mode and there we were able to achieve 100 and sub 100 nm, but after 193 nm we did not see much improvement at all.

So, 193 nm is the laser line that we are using even today and briefly there was some exploration to go to a 157 nm, but due to various technical difficulties in photoresist development, stability and economy of scale and so on. So, that did not catch up. So, we are still using 193 lithography, but you can see there is a new technology that is called immersion that has emerged to even reduce their features further, but the light source remained rather same.

But now if you want to go to 10 nm and below, we need to also reduce the wavelength. So, the technology that we are looking at is extreme UV . So, things are in an alpha and beta stage right now, we have not seen any production tools yet, but in a research and development is actively done in this region. But in this lecture we will limit ourselves to looking at 193 nm and then how people are evolving this process. So, as a takeaway from this slide we are reducing the wavelength in order to achieve resolution.

But there again there are challenges in not just reducing the wavelength, but you should have associated resist, lens and other optics should also evolve. So, in this case the resolution we are only attacking wavelength. So, we are trying to reduce your wavelength so, that we can reduce your pitch.

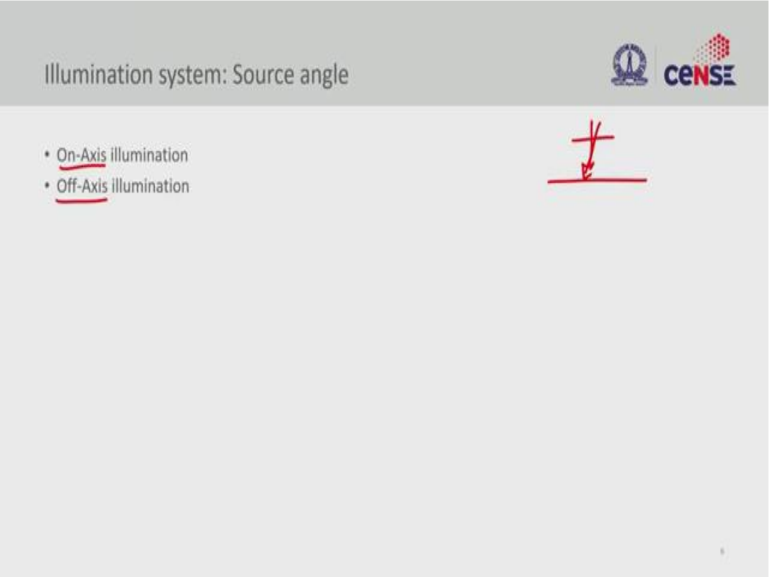
(Refer Slide Time: 07:07)



So, the next thing is about the source itself the elimination system is not just your wavelength, but also the shape of the source, in particular. So, we have couple of options here, what we call conventional circular light source. So, there is a circular aperture that takes in, but you can also change the shape of this light source. One can use annular; it is a ring like geometry and then you can have quasar, dipole or quasar or quadrupole. So, this is called quadrupole illumination.

So, what is the purpose of doing this sort of varying source shape? The primary reason in using different type of light source shape is to engineer your diffraction. So, when you are having conventional light sources, you will have diffraction shapes according to your light source. So, when you change the shape of the light source, you also change your diffraction and also unnecessary stray light going through this. So, this will increase your image contrast. So, that is something that we saw earlier MTF i.e., image transfer function. So, that transfer function improves, that is what we achieve by improving your light source shape.

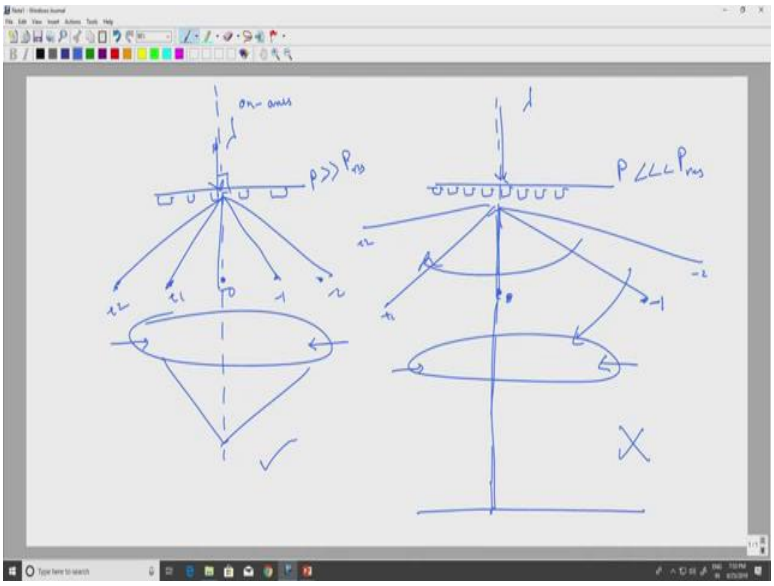
(Refer Slide Time: 08:41)



And then the next thing is about the position of the source itself. So, far we always looked at either the light source is either perpendicular and if you remember looking at the non-idealities, we also saw non perpendicular illumination there we had some oblique incidence. So, this is called the partially coherence .

So, the coherent light will have only one angle of incidence, but here if you are using a light source of certain shape, you will always have some partial coherence not just from the light source itself, but also the positioning as well. So, here we deliberately do some on-axis and off-axis illumination. So, let us look at what do we mean by on-axis and off-axis illumination.

(Refer Slide Time: 09:39)



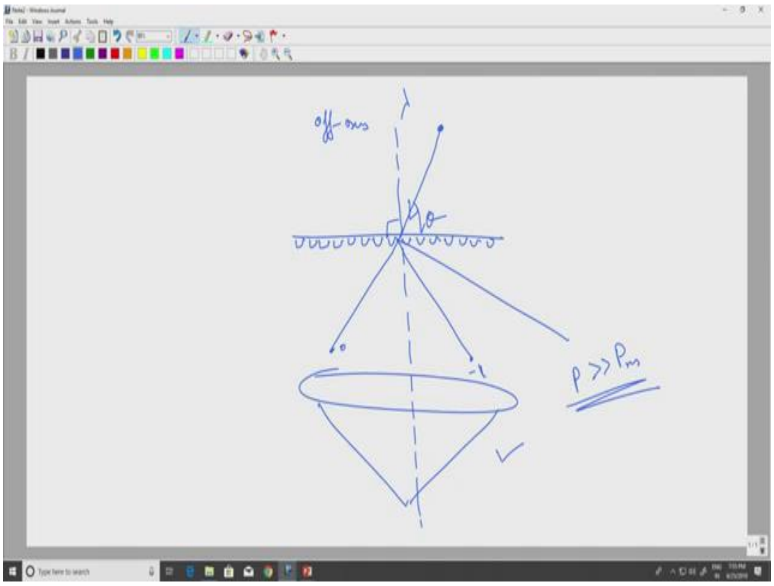
So, if I have a light source sitting here and then I have my mask and then when I illuminate it, this is on axis. So, the optical axis is straight here. So, this is on-axis. So, in on-axis illumination it is a perpendicular illumination and then what you get out of this mask is going to be the diffraction pattern. So, that we all know. So, that your lens is sitting here and then you will have your diffraction orders coming out. So, this is your zeroth order, +1, -1, +2 and -2. So, this is how you get it and then whatever falls within the numerical aperture, you will collect that and then image it.

So, now if I get a situation where your dimensions are reducing; that means, I have a very small pitch. So, we know that when you are illuminating these small pitch structures, anyway you will have your zeroth order, but your first order itself is going to be outside. So, I am unable to capture any of these orders . So, I am only getting the DC here. So, there will not be image formed of this because I am missing both the orders. So, in the imaging lecture we saw that you need at least one order that should be captured through your lens in order to make the image. So, the interference pattern you need 2 beams. So, now, I only have this zeroth order beam coming through the system. So, in this case you will be able to image.

So, what can you do with such a system because the wavelength is fixed. In both the systems wavelength is fixed, but here your pitch is smaller than $P_{resolution}$, but then you will say like I cannot print this particular pitch anymore. So, this is my limitation of the system.

This is thinking from the optics point: is it possible to bring 0 and +1 or 0 and -1 into this image plane. So, is it possible to do that? So, that is the question here. So, if you want to do that this whole diffraction pattern should be tilted. So, how do you tilt that? So, that tilting is done by doing off-axis illumination.

(Refer Slide Time: 13:09)

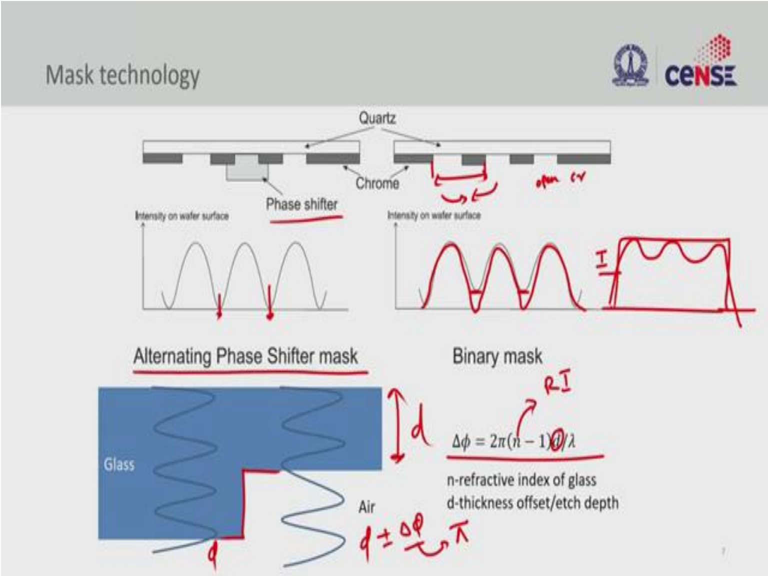


So, let us look at off-axis illumination. So, now, I have this dense pattern that I wanted to illuminate and then now this is the optical axis. The reason why we call it off-axis because the illumination is now coming from this side. Your light source is at an angle now. It is not anymore perpendicular.

So, when I do this my zeroth order is going to go like this, but my first order will be here and then my lens can capture zeroth and +1 order. So, I do not really care about the other orders because I am interested in only 2 orders which is good enough for me to get the image. So, now, because of this angle I am able to bring in both my zeroth order and my first order here.

So, with this off-axis illumination I will be able to image even the pitch that are greater than $P_{resolution}$. So, you will be able to image even with the given optics given wavelength just by tilting the axis. So, this is what we call off-axis illumination. So, not just the light source wavelength you can also position the wavelength in order to get the patterning done.

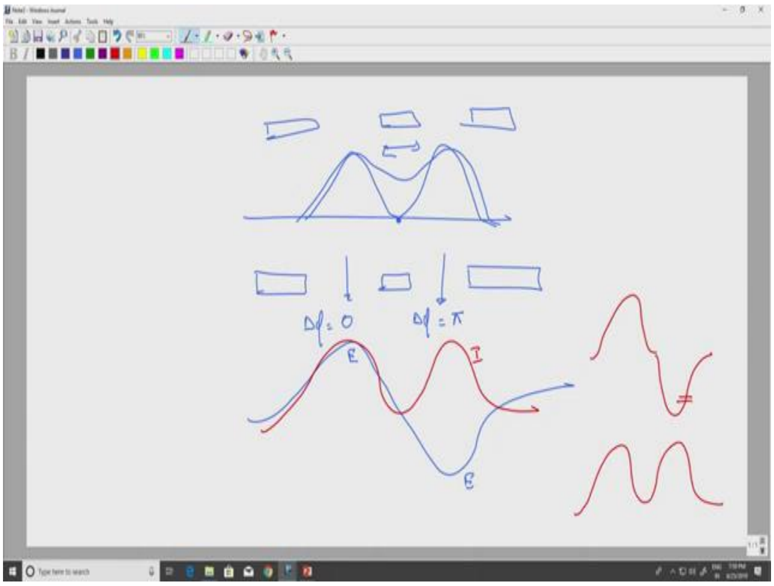
(Refer Slide Time: 15:04)



So, this is what we do for light source. Let us look at the mask technology itself. So, the mask technology has evolved over time in order to make better patterning for instance this is the binary pattern. So, you have chrome and then you have open area here. So, if the dimensions are very close, if the pitch is very small what will happen is the light from the adjacent open regions are going to overlap and then they will create this.

So, ideally you want something like this, the interference pattern should be 0, but you will not be able to get 0 when the pitch is very small because you have interference from the adjacent opening. And if it is very severe you will have something like this and if my intensity threshold for development of the photoresist is somewhere here, I will not be able to reproduce this, this will almost look like a pattern like this. So, I am unable to reproduce it in this case what we do is we use a phase shift mask. So, let us look at how this phase shift works.

(Refer Slide Time: 16:34)



So, if I have the opening something like this, let us look at the electric field. Electric field can be positive and negative. So, the field is like this let us say in this case and then also a positive in this . So, when they become closer this distance is reduced now. So, what you expect to see is something like this and then you will go into the region, where you will not be able to reproduce the image at all because you would not be able to reduce the power here.

So, in other terms you are going beyond the resolution limit. So, what we are proposing here is, why don't we change the phase of light coming through this opening. So, here the phase difference is 0 here the phase difference is π so; that means, the electric field will look something like this. This is the electric field, but the intensity will look like this.

So, this is the electric field (E), but the intensity of the light will look something like this. So, this is the intensity ($|E^2|$) is going to have opposite phase. So, this is how I achieve better resolution by changing the phase here. So, this is what we call phase shift mask.

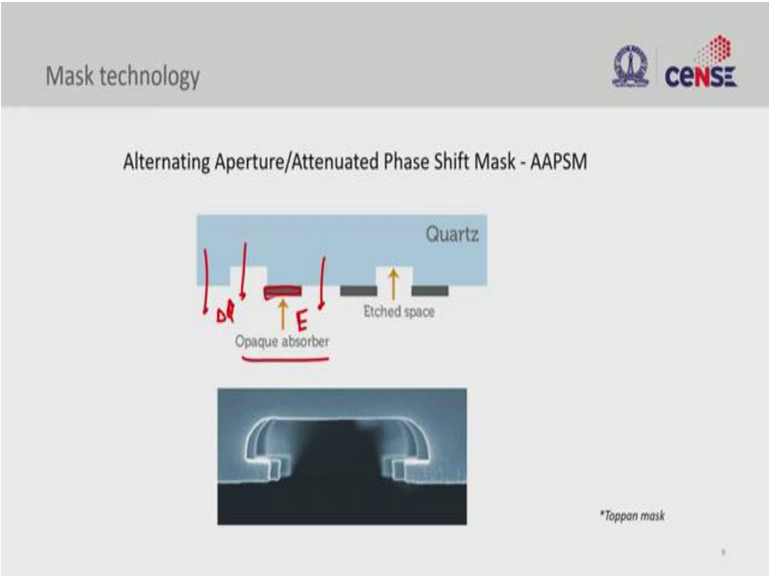
So, the adjacent one I am putting a phase shifter. So, this phase shifter will pull my amplitude down. So, how do we achieve this phase shift? by just adding an additional optical path. So, that is what is mentioned in this alternate phase shift mask, where you do not use any chrome at all . So, you use only glass and you are using glass of different thickness. So, here you will have ϕ, you will have $\phi \pm \Delta\phi$ and this $\Delta\phi$ you want it to be π and this π difference will come from this thickness difference and that is what is mentioned here. The phase difference is given by the formula,

$$phase\ difference\ (\Delta\phi) = \frac{2\pi(n-1)d}{\lambda}$$

Where n is the refractive index of the material, d is the thickness offset/etch depth, λ is the wavelength of the source.

If we want to get a certain phase difference, in this case π you can work with your thickness of your glass layer or you can play with your refractive index. So, you can do this offset and then once you do this offset, then you should be able to get the required phase shift. So, this is a simple way of achieving better modulation in your intensity by using phase shift.

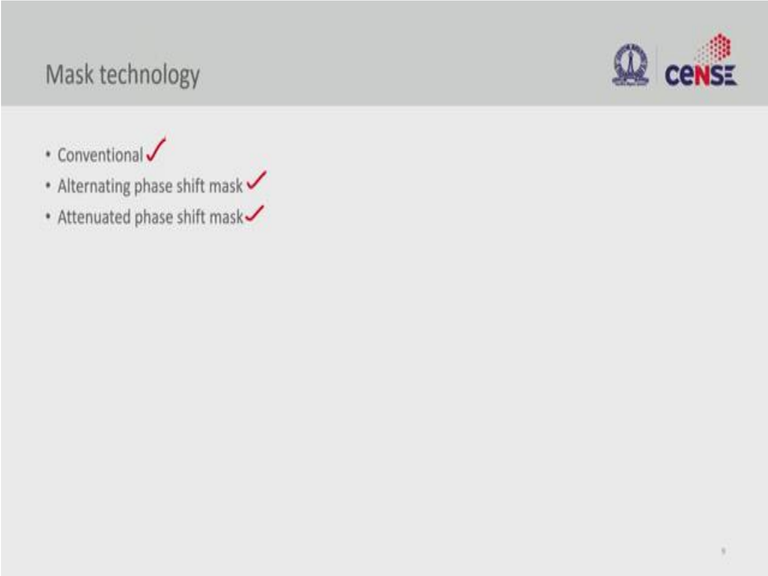
(Refer Slide Time: 20:02)



And there is something called alternating aperture attenuated phase shift mask. In the previous slide we saw only phase shift being used between two, but here you also put an attenuator. So, this is a very complex mask. So, here it contains transparent, partially transparent and absorbing material. So, you can do attenuating light here. So, what we are trying to achieve here is, you get the light modulation by using phase shift here and in this case you are using the just a power difference between these two.

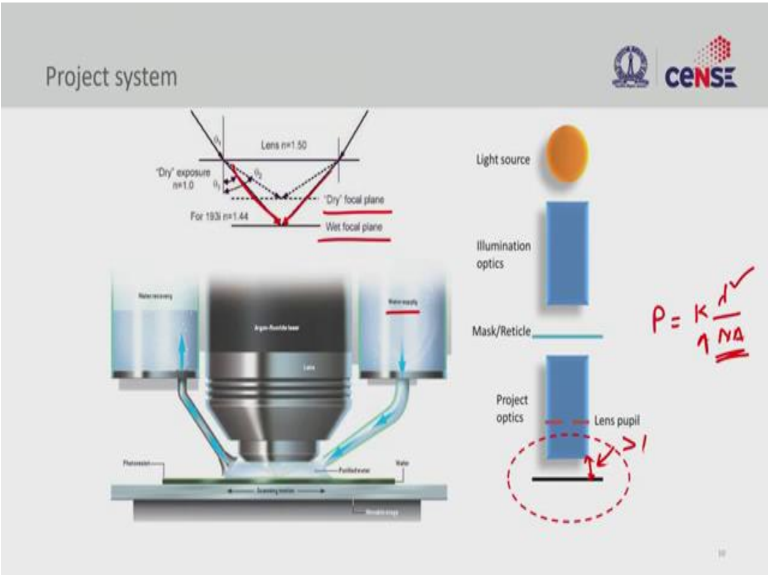
So, a complex mask could be built by using this technology to achieve better resolution. The only downside in this kind of advanced mask is the circuit design itself. When you have a structures that are very close to each other, managing those phase shifts and the absorption is going to be a challenge, but nonetheless if you have a repetitive features your phase shift mask or attenuated phase shift mask or advanced phase shift masks are going to be very useful in achieving a required resolution.

(Refer Slide Time: 21:32)



And as I mentioned you can either use conventional technology, you can use alternating phase shift mask; that means, you do not use any chrome. So, the alternating intensity patterns are given by just a phase shift alone and the attenuated phase shift is where we use chrome or we can use partially transparent as well. So, these are all the technology that we use in masks in order to improve your resolution.

(Refer Slide Time: 22:03)

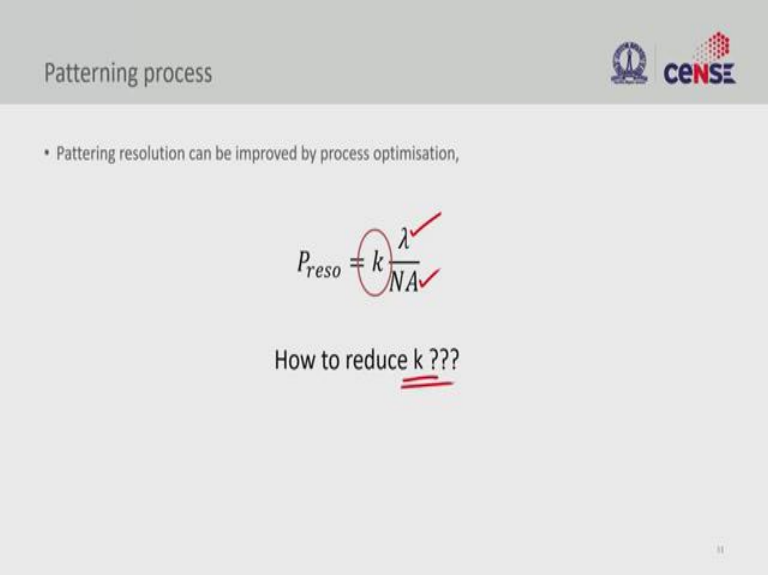


So, the next thing is about the projection system. So, what is the change that we can do in this projection system in order to improve the less resolution? So, on the right-side it is a familiar image. So, the gap between your projection system and the wafer makes a huge difference. So, this is where your numerical aperture of your projection system becomes very interesting. So, your resolution is given by kλ/NA we have seen how to improve λ, but now let us look at the NA.

So, we want to increase the NA; when you increase the NA your resolution can be better. So, in order to increase the NA you have to decrease or remove the air from this gap and then put a material that has refractive index greater than 1. So, the only way to do that is either you put a liquid (water) in this case or you use some sort of a oil and then when you put this immersion fluid in, your imaging is going to be better.

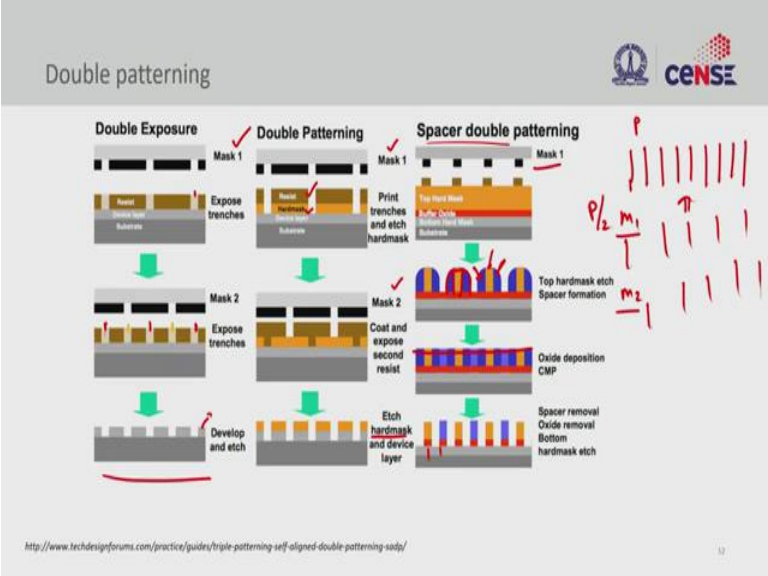
So, when you put a fluid between a your lens and your objective lens that you have and your slide, you are naturally improving your numerical aperture and your image quality as well . So, here you say the focal plane will change in the presence of a fluid, but that is something that you must take care of when you are optimizing the image and the other important thing is the angle . So, the angle at which you get also gets better. So, instead of a shallow angle you get a deeper angle so, that you can image them better.

(Refer Slide Time: 24:15)



So, this is a change in the projection system and now we have seen both λ and NA modification and there is one more factor that can help us in improving the resolution that is ‘k’. So, as we saw earlier ‘k’ represent process optimization and process parameter. So, if you reduce your ‘k’ you can also improve your resolution. So, how do we do that?

(Refer Slide Time: 24:42)



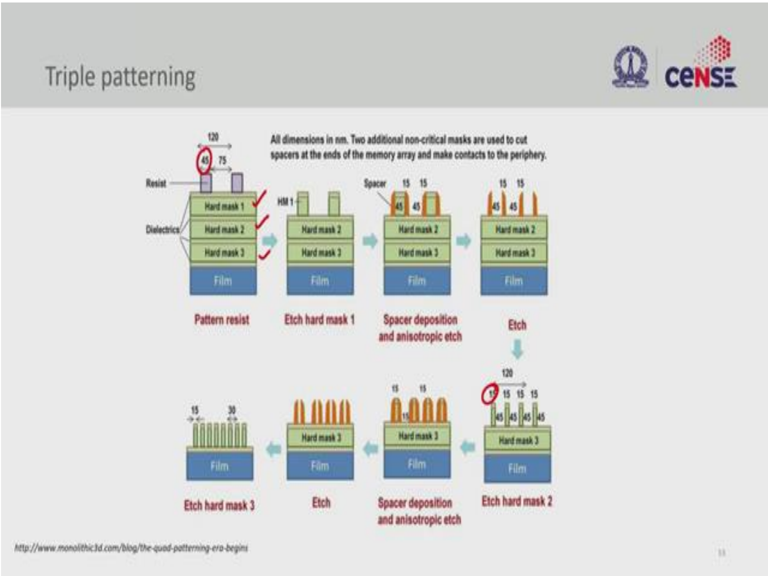
So, let us look at that. So, one way of reducing ‘k’ is by doing double patterning. So, here the illuminating optics and the resolution of the illumination system is constant. But what we do? We do repetitive patterning. So, you divide your pattern density into 2. I have a very dense pattern which is beyond my resolution. So, what I do is, I divide this by 2 and make 2 masks: mask 1 has this pattern and then mask 2 has the interlay. So, now, if I image m 1 and m 2 on top of each other I should be able to get what I want. So, that is what this double patterning is all about.

So, you first illuminate mask 1. So, you can see here, this is mask 1 and this is the mask 1 pattern and then mask 2 comes on top of it. So, this is mask 2 and when you put mask 2 one on top of mask 1 the final image is double the pattern density. So, if you develop it you will end up with the resolution better than the mask 1 and mask 2 that you used.

So, the only important parameter that one should be careful here is the alignment . So, in the cartoon you can clearly see that it is easy to align, but in technology wise you are looking at resolution improvement by increasing the load on the alignment accuracy. So, one need to have very high alignment in order to do that. So, the other way of doing it is by transferring it to an intermediate layer. So, this is the resist I am transferring it to a layer called a hard mask which will capture this and then I am doing it 2 times again, mass 1 and mask 2 and then I am using that hard mask.

So, I do not use the photoresist anymore here, I use the hard mask and then transfer it to the device layer. And there is one more technique called spacer double patterning. What do we mean by spacer? This is a little complex process where I use mask 1. There is no two mask process here there is only one mask, but what I do is I make a pattern first and then coat material on the side . So, I am just coating the material on the side like a spacer. So, I get this spacer done and then I remove whatever material I had on the sacrificial layer and then you can take this pattern and then planarize it and then remove all the sacrificial layer and then I should be able to get a denser pattern here. So, this is spacer had defined the double patterning.

(Refer Slide Time: 28:14).

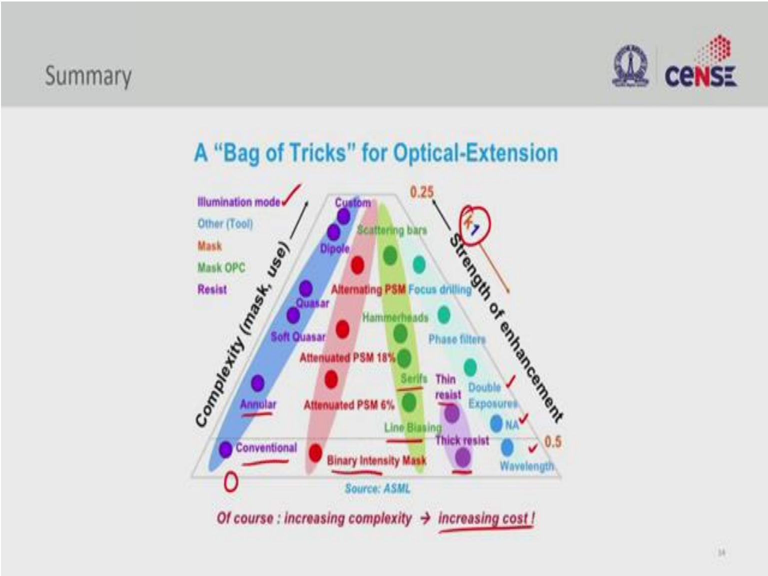


So, how do we even increase it beyond this double patterning? So, you can do triple patterning. There is no need to go through each and every process here because this is replicate of whatever we saw earlier and there is a spacer based patterning, but the only difference is we have multiple layers of hard mask, we go from mask layer 1, hard mask 2, hard mask 3 so, that you get the best of these layers and then you improve the resolution here.

So, you take this 75 nm pattern and then make it into 15 nm pattern. So, this is the improvement that one can get by using this sort of double patterning and triple patterning.

The downside in doing all this is at higher level patterning it is the cost of adding multiple layers having alignment that should yield the kind of a resolution that you are looking for and this all these criteria adds up to the cost . That is the reason why this high resolution patterning by improving ‘k’ always adds up a huge in terms of processing cost.

(Refer Slide Time: 29:30)



And in summary this image captures how one could improve the resolution of the optical lithography process, the various parameters. So, you can use different type of an illumination mode, we saw conventional illumination: a circular illumination, annular, quasar and so on and then you can use different type of masks. So, you can use binary mask or use phase shift masks and so on and then you can also do assist features. So, we saw in mask development, how to improve the resolution by adding assist features and so on. You can go for thinner resist as well that should yield better resolution and overall improvement in ‘k’ .

So, that is what one can also look at, where you use a wavelength or any double exposure. So, all those things can be used to improve. So, you can make it more complex and get the required dimension, but this will all lead to increase in cost. So, whether the economy of scale is justified in achieving the required resolution is the question here. It is not about the limit, it is about the cost associated with this. So, with this we come to the end of the resolution enhancement discussion.

So, where we saw it is possible to attack a different system parts to achieve the resolution, we saw increasing your NA will also improve your resolution, decreasing your wavelength is also going to improve your resolution, but then you can also develop processes by using double patterning, triple patterning or quadruple patterning to improve your ‘k’ .

All these parameters could be attacked in order to improve your resolution but as we already saw the downside in doing so, is the complexity in the system and additional cost. So, whether all the resolution enhancement is justified in the cost and complexity we are spending here. So, based on this one would take a call whether I can use this resolution enhancement technique in order to yield the resolution that will yield my economy of scale. So, this is going to be your deciding factor in resolution enhancement.