Advanced Neural Science for Engineers
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Lecture 26
Lithography Optics - II

Hello everyone, welcome to this linked TA class on Lithographic Optics. First class, we have clearly understood that how optics is very important, how it is being evaluated in terms of resolution, how resolution is calculated, what is resolution, what is the depth of focus, how in actual practice or research a lithography affected resolution and all this thing. So, in this lecture, we will see that how we can go from micro to nano few micrometers to nanometers and quickly zap through the resolution enhancement technique.

However, resolution enhancement technique, if I start talking about, will take a lot of time to understand each and every resolution enhancement technique. It is a separate topic altogether, here the agenda of this particular TA class is to make you people feel that, there is a possibility or with the advancement in lithography optics or with the advancement in resolution enhancement techniques, we can go from micrometer to nanometer using one particular method or aspect. So, this all things I will try to cover quickly in this particular short TA module. So, this is like, quick recap of what we have seen.

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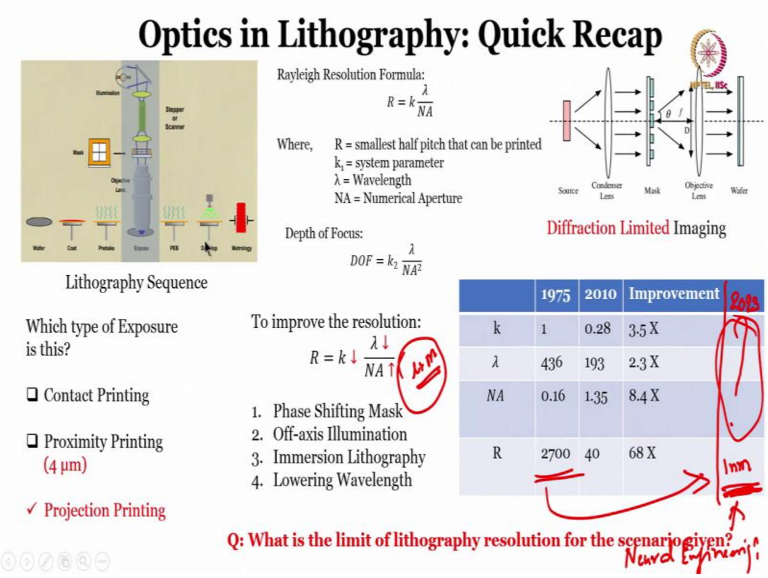

Optics in Lithography: Quick Recap

Lithography Sequence

Rayleigh Resolution Formula:

$$R = k\frac{\lambda}{NA}$$

Where, R = smallest half pitch that can be printed
k_1 = system parameter
λ = Wavelength
NA = Numerical Aperture

Depth of Focus:

$$DOF = k_2\frac{\lambda}{NA^2}$$

Diffraction Limited Imaging

Which type of Exposure is this?

☐ Contact Printing

☐ Proximity Printing (4 μm)

✓ Projection Printing

To improve the resolution:

$$R = k\downarrow \frac{\lambda\downarrow}{NA\uparrow}$$

λ+M

1. Phase Shifting Mask
2. Off-axis Illumination
3. Immersion Lithography
4. Lowering Wavelength

	1975	2010	Improvement	2023
k	1	0.28	3.5 X	
λ	436	193	2.3 X	
NA	0.16	1.35	8.4 X	
R	2700	40	68 X	1nm

Q: What is the limit of lithography resolution for the scenario given?

Neural Engineering!

This is a litho sequence out of which what is important task, what is important sub process which is important process? Lithography. In lithography which is important sub process? Optics, why it is important already discussed. And this is which kind of printing that we already discussed that is a kind of a projection printing. Furthermore, this is the formula of lithography, we have already seen how to improve this particular when I say how to improve means, it can be the lowest fine finer microstructure which we can faithfully produce on the wafer.

And this is again a simplistic toy diagram, why I saying toy diagram is because in actual practice if you see one litho system which is like almost 6 to 7 feet of height, but this is just a simplistic diagram for understanding purpose, that is what I said I want you people to feel or understand that how this particular technique or how a litho works. So, this is another illustration of that. Again, very important point is, this is a diffraction-limited imaging. Probably for the last time, I will tell you the stop-down approach because it is important from microelectrode array development relies on fabrication, relies on litho, relies on optics. In optics also in current research, we are still limited by diffraction.

Diffraction, all of us would have studied in our plus 2 that what is diffraction, what is a reflection, what is refraction. If not, I would strongly advise you to just check it once because that will help. Also, along with that, I would like you to just brush up your basics of interference, what is constructive and destructive interference etcetera, it will help. It will be a constructive, interference if you go through that.

So, this is like a depth of focus, you can calculate using this, already discussed how much you can move or how much freedom you can take, or how much tolerance is allowed in terms of movement of objective lens, it is nothing but depth of focus. All are empirical formulas, so, there is no clear-cut derivation for that, again, when you change some of the aspects of this, this result formula might get changed. So, there are models for that to model that and all. Improve the resolution, which is our main topic in this particular lecture is your resolution enhancement technique, you can use this particular formula:

$R = k(\lambda/NA)$

Now, you know mathematically also and in actual practice also, which parameter can be modified and resulted in which kind of technique and also this is like a overall growth what has happened to the course of time. One last thing which I have written at that time to give you people an idea, we are in 2023 and even 1-nanometer microstructure can be fabricated.

However, this 1-nanometer is appropriate for which application of neural engineering, that you can do a survey why I am saying this is, when you want to record, when you want to record from smaller and smaller, when you want to resolve smaller and smaller region of the brain, it gives you more and more information confined to that particular area. And also, you need to understand the charge density and all this thing, you cannot put very, very thinner interconnects or wires which is in which a bio potential is riding which is of very high value.

So, there are research for that and you can check whether this particular nanometer width is good enough to record response from few neurons or not. Because your target if you are targeting a neuron based response, it is very, very, very small in dimension, you require equally small dimension, acquisition system or acquisition device to get that particular thing. So, that is why in 1 nanometer you can see the difference between 2700 nanometer to this nanometer and what is being done now. So, this is all about today's TA class.

So, again recap all these things you have already seen, understood and this is the current picture and even current picture and how it has been done. Again, we will go quickly through all the resolution enhancement techniques. So, let us move ahead, what is the (result), this is what we have discussed last time, that you improvise each and every parameter and what is the limit of lithography. Now all of you would have considered some or the other parameters for k lambda and NA. But irrespective of all the parameters, it would be few micrometers. I am not taking any particular case here.

But based on your understanding about this parameter and the based on your understanding about this parameter, which parameter is more optimal, you would have taken this particular thing and you would have got this particular resolution. So, this is micrometer again, but people say that fabricate found is a fabricated 1 nanometer how it is possible. So, only this thing is also not enough. But this is the only thing we have to pattern this particular thing. So, how can we go even more by improvising this particular system, what to improvise, how to improvise, what are the things used, we will see this in this class.

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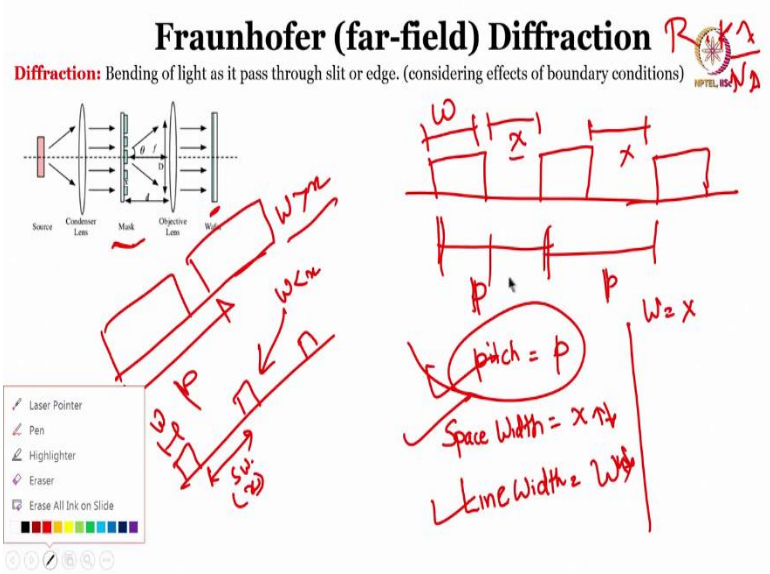

Fraunhofer (far-field) Diffraction

Diffraction: Bending of light as it pass through slit or edge. (considering effects of boundary conditions)

So, let us move ahead. I told you to check the Fresnel and Fraunhofer diffraction, when Fresnel diffraction should be used and Fraunhofer diffraction will, both are diffraction then why there are two types. So, based on your application, you need to consider whether it is Fresnel or Fraunhofer. Now, in this particular application, we want to produce this mask on the wafer. So, this mask has this space and line. Just to give you an idea, if this is my structure, which I want to present, this is another structure this is very, very, basic nomenclature for optics and especially litho optics. You want this repetitive three structure, consider this as a 3 wires guiding some current or some potential something.

And this distance remains constant, I will name it as p, this distance is x, same holds here also; this is x, this is p. So, I just want to know the convention. This p is known as pitch, which is nothing but p, this x whatever you see now, here there is a space between two structure. So, this x is known as space width x and this thing not written here, let us show it by w. So, this w is nothing but your actual structures width known as linewidth, so, that is nothing but w. So, this is like a normal convention which is used a lithography.

So, while explaining this, if I say space width, you should not feel that what is space width? What is line width? What is pitch? If you remember in the resolution formula:

$$R = k(\lambda/NA)$$

R = k(λ/NA)

I have already mentioned about the half pitch that half pitch is nothing but this and this distance between this. Again, here as per this example, we it almost appears that w equal to x, in other term space width is equal to line width, is it always the case? No, that can be a different structure like this.

This is your line width, so here is space width is much, much bigger. Space width in our terminology let us say x whereas the line width w is very small or there can be structures where you can find this kind of structure where your this is anywhere your p, when you are here this is the case w is less than x, I am talking about this case whereas here w is greater than x.

That is why you are based on your application your line width and space width will keep on changing. That is why, when you talk about resolution you should consider pitch, it is just a brief idea, but before coining all this term, I want you people to understand that what is line width, what is space width, what it pitch.

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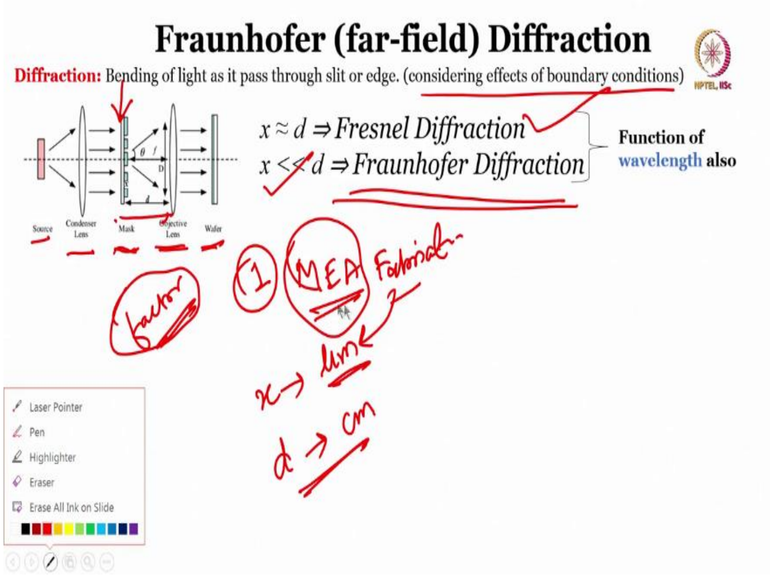

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$x \approx d \Rightarrow$ *Fresnel Diffraction*

$x << d \Rightarrow$ *Fraunhofer Diffraction*

Function of wavelength also

So, this is like again our main a simplistic diagram to explain the litho process, optical illumination, condenser lens, actual practice, there are multiple of lenses to guide the light in exact way you want. Mask, objective lens and wafer. This is like a overall picture of that which you all have you now understand. What is diffraction? Bending of light as it passed through slit or edge, considering effects of boundary condition.

So, again here bending of light will happen in the edge where is the edge, edge will be the pattern on the mask. So, based on the pattern on the mask, that light will travel, light will get diffracted and based on the diffraction level of diffraction, whether it will be received by this objective lens or not and then further it will get, it will travel to your wafer this is the overall idea.

Now when to use Fresnel and Fraunhofer diffraction. So, they are saying x when x is almost equal to d, d is the distance between mask an objective lens. So, d is the distance between mask and object lens, in this particular case of we will see when which one is applicable here our main application in advanced neurosciences MEA fabrication. Micro electrode array fabrication and there it has a dimension of micrometer, why am I saying again this thing now, because this tells me that the dimension on this mask, your required dimension will be in terms of few micrometer.

Again, you might there might be some factor that you have to consider, let us say here it is 1 micrometer here it gets reproduced by some multiple of that micrometer or few, if it is 10 micrometer here, here you might get 2 micrometer that is based on what is your multiple factor of this. It also depends on power of lens and all this thing, but if this is your x is in micrometer. And as I mentioned lithography system is like a youth system, which is of the size of 6, 7, 8 feet. And that person handles it.

So, that will be as controlled or control computer will be there at the same height of a person around 5 feet or something. So, the this distance or this is your d, small d, will be at least few centimeters. So, for this particular MEA fabrication application, this thing holds. I hope all of you understand and are with me, because your MEA dimensions will be in micrometers this is your x dimension on your of space width it seems here, dimension of your space width or overall width it will be few micrometer whereas this distance can be a few centimeter that is why we are applying a Fraunhofer diffraction not the Fresnel diffraction.

Like this, there is always a basis of what you are considering or in research, whenever you are considered there are multiple ways to deal with a particular research problem, why you are selecting that particular way it is very important and there should be a logical scientific reason behind that. So, you understood now that why we are using Fraunhofer diffraction.

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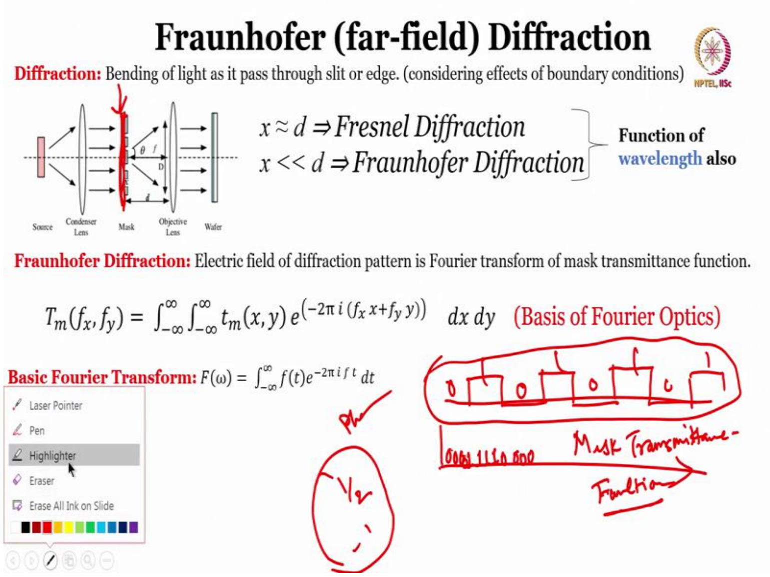

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Fraunhofer Diffraction: Electric field of diffraction pattern is Fourier transform of mask transmittance function.

$$T_m(f_x, f_y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} t_m(x,y)\, e^{(-2\pi i\,(f_x x + f_y y))}\; dx\, dy$$ (Basis of Fourier Optics)

Basic Fourier Transform: $F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-2\pi i f t}\, dt$

So, will move ahead. So, this thing you have to consider it is very important that Fraunhofer diffraction whenever Fraunhofer diffraction happens. The diffracted pattern how it is looking like. Now all this thing as I mentioned light, light is electromagnetic wave. So, then it will get diffracted by something there on musk. So, then what happens is, this should be this pattern whatever is there in mask needs to be converted into some mathematical form, let us say this I am considering this particular mask right now, I am drawing the same thing here some line width some space width some line widths, consider it as the same.

Let me just redraw it again. There is some line width here space width, again some line, there is some space, again some line and there is some space and bring it only 3 instant here 5 are there. So, we need to quantify this thing, very important, how to quantify this thing. So, this looks like a square wave for electronic students it is look like some square or rectangular pulses. And I am just forming it as a consider it is as digital form. So, there is nothing here. So, till now 000. At this point of time getting 111. Again 0000, in between also similarly, you can say there is some edge and all that time there will be a transition from 0 to 1 same thing.

So, this is what 0s and 1 is known as your mask, transmittance, transmittance function. Again, I will not go into the detail but what is mass transmittance function? This is 0 this is 1 this is 0 this is 1 this is 0 this is 1 this is 0 this is even further it goes it is 1. So, you are in a way telling or quantifying that what is your input which is coming to this surface, that is your electrical light and then from this surface your desired pattern will be quantified in terms of this number.

Now, one more question this is 0 and 1 can it be 1 and a half, can it be minus 1? This thing will be answered in one of the resolution enhancement technique known as phase shifting mask, we will come to that later. But for now, the point is you should know what is number.

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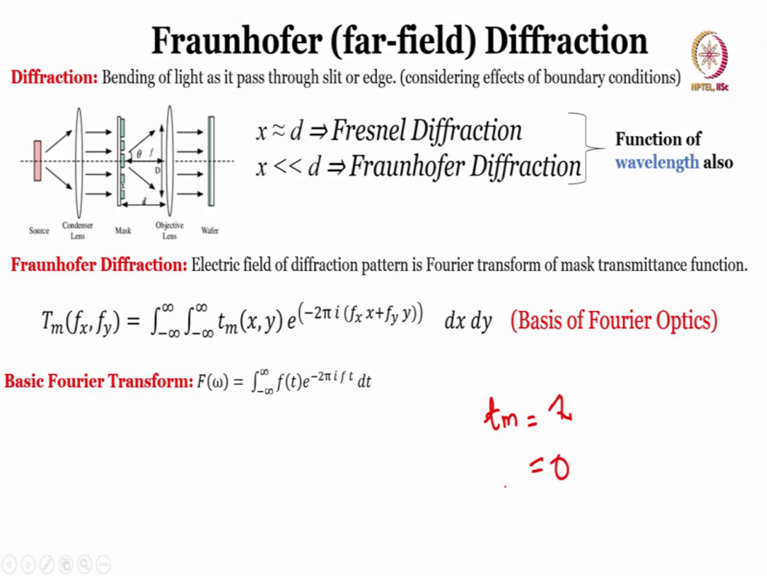

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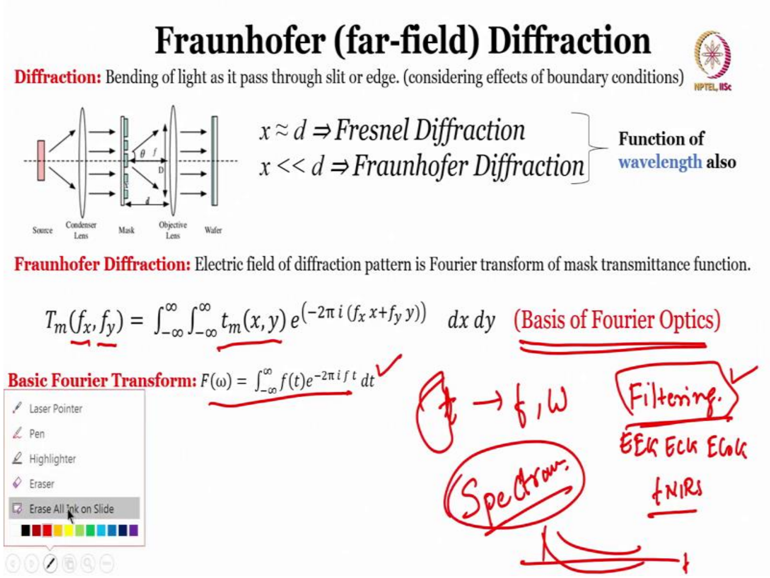
$t_m = 1$
$= 0$



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Basic Fourier Transform: $\underline{F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-2\pi i f t}\, dt}$ ✓

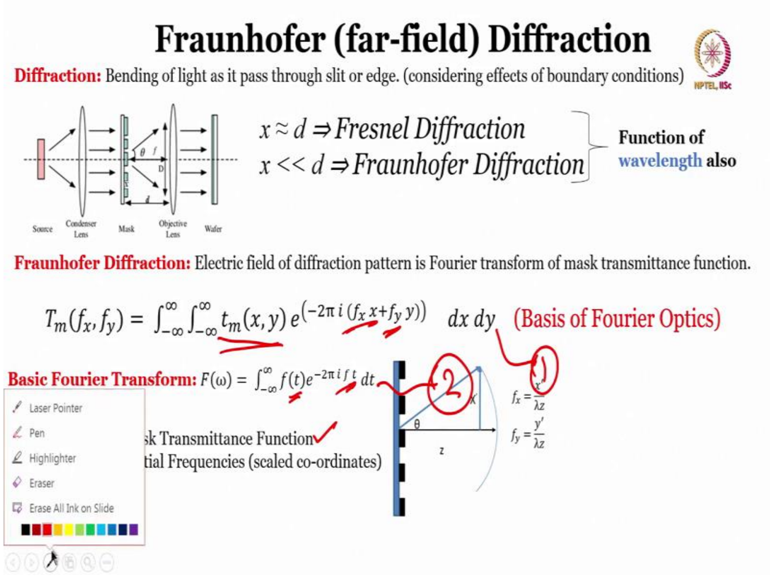
$t \rightarrow f, \omega$

Filtering. ✓

EEG ECG EGG

fNIRS

Spectrum.



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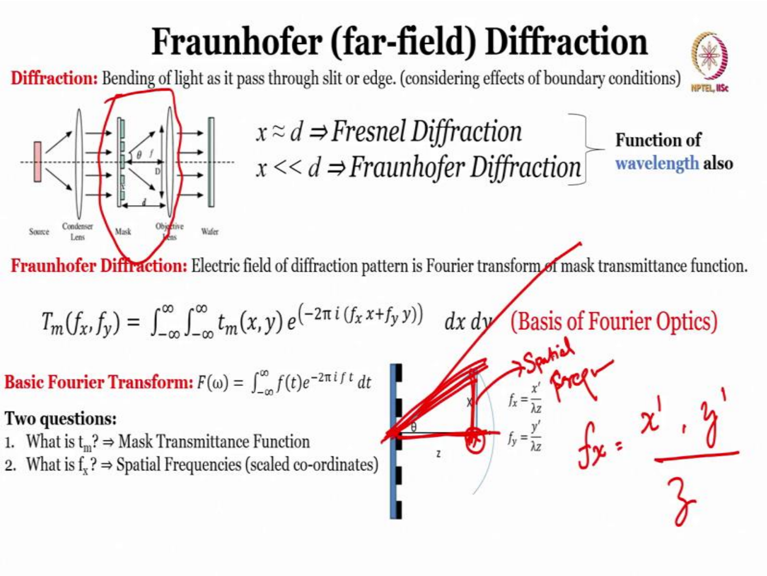
$f_x = \frac{x'}{\lambda z}$

$f_y = \frac{y'}{\lambda z}$

sk Transmittance Function ✓

tial Frequencies (scaled co-ordinates)



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Two questions:

1. What is t_m? ⇒ Mask Transmittance Function
2. What is f_x? ⇒ Spatial Frequencies (scaled co-ordinates)

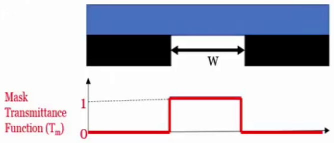
$f_x = \frac{x'}{\lambda z}$

$f_y = \frac{y'}{\lambda z}$

→ Spatial Freq

$$f_x = \frac{x', y'}{z}$$

Diffraction limited Optical Lithography



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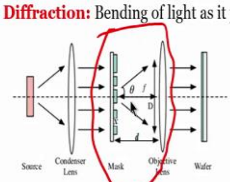

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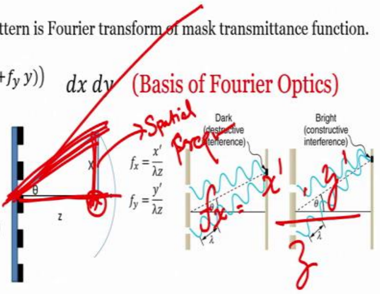

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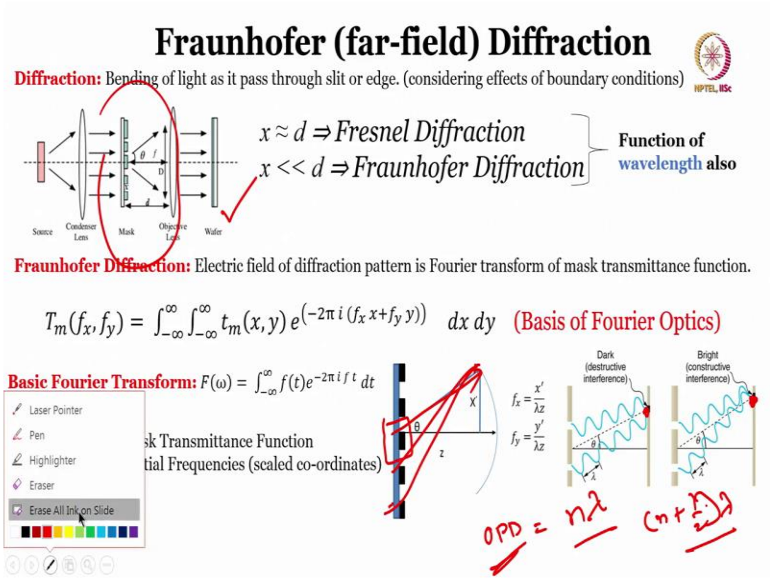

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$f_x = \frac{x'}{\lambda z}$
$f_y = \frac{y'}{\lambda z}$

OPD = $n\lambda$ $(n+\frac{1}{2})\lambda$

I want you people to realize what is mass transmittance functions which is your tm. So, when light passes through that particular thing there will be one value when light passes let us say 1 and when light cannot pass the 0 or it can be the either other way around as well. Basically, you want to quantify what is the final thing which is passing through this particular mask. So, it adds your subjectivity or it adds your desire patterns quantification into the picture that which light is getting reflected which is not, that is all is your tm, if you cannot understand we will see the example in the next slide is very easy, but this is what you can see this fx and fy is some coordinates or spatial coordinates.

Now, this is known as Fourier optics, why Fourier optics? So, if you see this particular formula alone, you can get an idea that was similar to Fourier transform, what is Fourier transform you have already covered in your engineering I hope and then what it does is it converts time domain thing into frequency domain. Now, if I say frequency, it can be angular frequency it can be this frequency also, but the thing is basically whatever the time domain signal you need to map it into another domain to get more information out of this.

Where is this useful for neural science it is immensely useful for neural science because when you record any kind of signal, you need to perform filtering after that, slightly I am deviating from this litho optics topic, but as it is relevant to neural science, I cannot resist myself I need to inform you that this transformer Fourier analysis when you record any of the signal be it your bio potential EEG or ECG, ECG also ECoG, even FNIRs all these things once you record the signal, you need to pre process it you need to remove the non neural unwanted part of it. Filtering would be useful there, filtering would be based on your Fourier transform.

Post filtering and pre filtering, you should see something called spectrum. What is spectrum? Which component of frequency is more dominant generally it is like this frequency decreases as you go from initial, after a DC offset removal from lower frequency to higher frequency amplitude or frequency decreases. All this thing you can identify using Fourier transform and you can check whether the filters are applied properly or not by checking pre and post filtering spectrum.

Slightly off the topic, but it was important in the context of neural science. So, I just thought of covering it. So, now you do one thing this 1 big slightly difficult equation and name it equation number 1 and this is another equation which is a standard Fourier equation, try to see both the equation and compare what you see, and what are the differences between these two equipment?

First one very obvious is that equation number 1 has 2 variables it is a double integral whereas, equation number 2 has only 1 integral. So, that is like standard difference. So, that is understood to all of us that is fine, what are the other differences? Here, in Fourier transform equation number two, we have some function of time whereas, the above equation we have some function of mask. So, that is another difference.

And another thing is here we have an equation of some function of I said mask, mask is a some function of space or some particular region or space that is why here in times with respect to time we have time is multiplied, whereas, here we have some spatial frequency is multiplied, what is spatial coordinates and spatial frequency? I will come to that quickly. So, as I mentioned, we had 2 questions, what is tm? Here we know very well it is a function of time we have many signals which is a function of time whereas, here we do not know what is tm so, that I already explained you what is mass transmittance function, what is fx, here there is the relation where fxx and ft.

So, that spatial coordinates which you can see here, let me just clear it up for you for better understanding. So, this is your now from this thing we are already focusing on this thing you see things are getting problem is getting narrowed down immensely from developing MEA to just mask an objective lens, this is where we are. So, again as I mentioned, there is a formula for that this is x dash, there will be y dash also but we cannot see it is either going towards the screen or going inside the screen or coming out of that.

So, based on this distance z and how much it can allow the I mentioned if it is go beyond theta, it will go out of lens it will not take it. So, based on your maximum theta you are getting this coordinate. So, this coordinate is known as your spatial frequency or spatial coordinate, spatial frequencies. Again, it is a function of which thing your fx or your spatial coordinates is a function of your x dash also y dash also it is a function of the distance z. So, this is just a overview what is fx, fy, fz and all these things.

We will go in further how we will see only the one case. Let us even narrow it down a bit more, we have seen this much from litho MEA, fabrication we have come to this litho optics, from there we have come to only this particular aspect, which you can see here from there also let us just consider only one this one particular thing. So, and then how diffraction work just to make the things easier.

And also as I mentioned, due to this slit, it is going here due to this slit also there will be something due to this slit also there will be something when you have multiple waves reaching to 1 particular point there are possibilities of getting interfered and that interfered can interference can be destructive or constructive.

Now, how to decide whether there is a constructive interference or destructive interference, it will be a function of your wavelength, what is optical path difference OPD. If it is N λ or (N+1/)2*λ . When optical destructive interference happen, when optical constructive interference happens, I will not tell you, you can identify interference like class 2 physics very, very easy. You can revisit that and identify, same concept applies lithography and getting a proper imaging in one particular point. So, some of the very basic things which we learn in our plus 2 is very, very, very helpful when we talk about solving a big problems.

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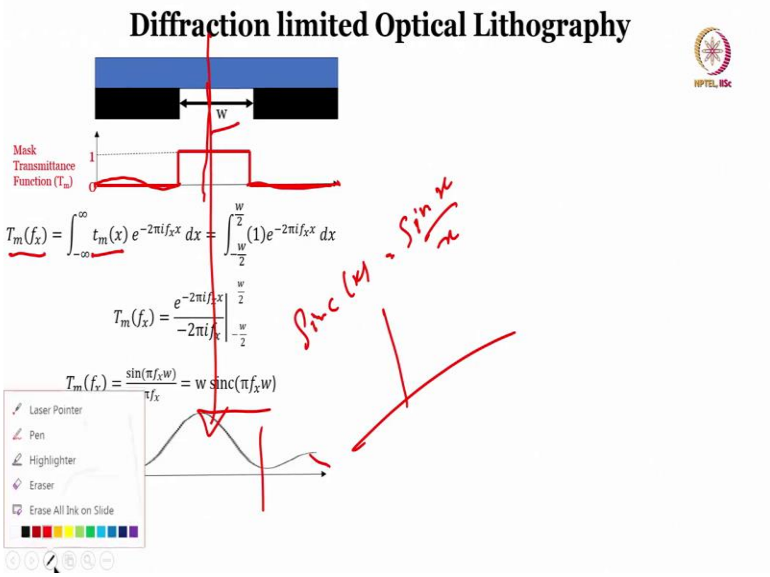


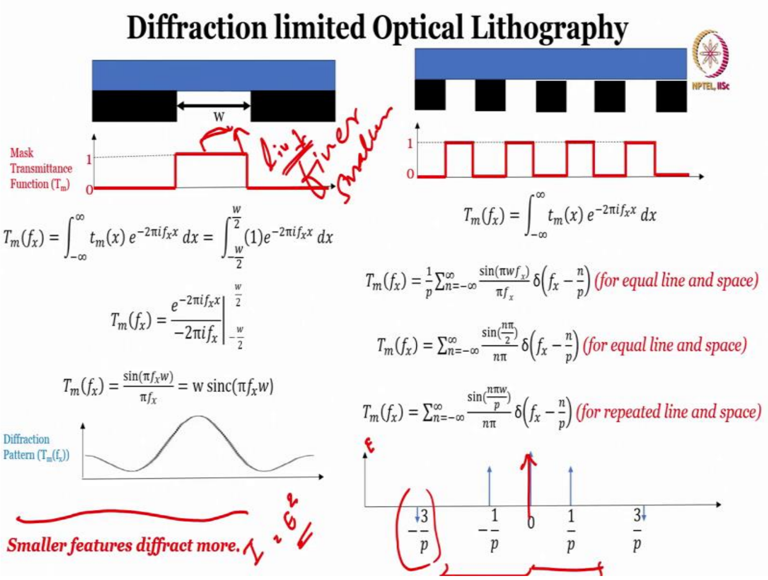
Diffraction limited Optical Lithography

$$T_m(f_x) = \int_{-\infty}^{\infty} t_m(x)\, e^{-2\pi i f_x x}\, dx = \int_{-\frac{w}{2}}^{\frac{w}{2}} (1) e^{-2\pi i f_x x}\, dx$$

$$T_m(f_x) = \left. \frac{e^{-2\pi i f_x x}}{-2\pi i f_x} \right|_{-\frac{w}{2}}^{\frac{w}{2}}$$

$$T_m(f_x) = \frac{\sin(\pi f_x w)}{\pi f_x} = \mathrm{w}\,\mathrm{sinc}(\pi f_x w)$$

$$\mathrm{Sinc}(x) = \frac{\mathrm{Sin}\,x}{x}$$



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$$T_m(f_x) = \int_{-\infty}^{\infty} t_m(x)\, e^{-2\pi i f_x x}\, dx$$

$$T_m(f_x) = \frac{1}{p}\sum_{n=-\infty}^{\infty} \frac{\sin(\pi w f_x)}{\pi f_x}\, \delta\!\left(f_x - \frac{n}{p}\right)$$ *(for equal line and space)*

$$T_m(f_x) = \sum_{n=-\infty}^{\infty} \frac{\sin(\frac{n\pi}{2})}{n\pi}\, \delta\!\left(f_x - \frac{n}{p}\right)$$ *(for equal line and space)*

$$T_m(f_x) = \sum_{n=-\infty}^{\infty} \frac{\sin(\frac{n\pi w}{p})}{n\pi}\, \delta\!\left(f_x - \frac{n}{p}\right)$$ *(for repeated line and space)*

Smaller features diffract more. $I = E^2$

So, this is like as I mentioned, let us just focus on one particular aspect which you can see here, all of what is mask transmittance function I already told you. This is a space width w, fullwidth. (())(24:54) that that is a P, that is a pitch full width. Now this is very, very simple mathematical calculation. We already know that your final diffracted pattern which is capital TM, which is a function of your mask transmittance function, which is small tm and this is the formula. Quickly putting up the values you see this thing is everywhere else 0 that is why I have shown in red color, everywhere else it is 0 only during this region that light can travel it is 1.

So, where, let us just keep it up y axis here minus w by 2 to w by 2 value is 1 rest everything it is 0. Again, this is small integral you can either calculate or you can pause the video calculate the integral and identify it is basically a sinc function, sinc function sinc of x sin x by x, how it looks like, how it plotting and all you can say something like this what I wanted to convey is there will be some minor lobes here and there, but main thing which is propagating here. So, this is like a very briefly I am explaining how this diffraction pattern comes out.

It is not only a function or diffraction pattern also there is a something called aerial imaging which will be covered in the next slide. And also, there will be not everything will be all the diffracted this is like everything gets diffracted from here, it is a formula of that, but there will be some spatial constraint that we want one between this and this only and all. We will come to that. So, this is the case of one particular open space width. What if there will be a repetitive of structure like this, this is more or less more used structure in the field of lithography. So, you can see that there is a multiple line width and space width, it can be equal it cannot be equal also.

So, I would like you people to do this exercise put the values here and you will get this particular thing. If you want to see the derivation, feel free to write us in the forum will prepare a derivation and share the link with you and for equal line and width and for repeated line and width there are different formulas this is nothing but a delta function. So, when you see this particular pattern, it will come something like this, diffracted due to this.

Now, when I say this this central part is the most highest intensity, and when you go away from the center, the intensity decreases, also you can see some of the value having negative intensity, all this thing is diffracted wave, further, in order to get the intensity this is again electrical fields diffracted electrical field, when you talk about intensity of light, you need to square it up. So, you will get the overall intensity of the light, falling to a which particular point, is there again, quick analysis.

One more thing, when you say a small this particular feature, you vary the width of this, increase it space width, so, your line width decreases. When your line width decreases, you want even a final feature or smaller feature, and repeat the exercise and check what amplitude you get. Now, this rule says that smaller features gets diffracted more, I want you people to mathematically check it once quickly, when you just want to put a pen and paper instead of w you can have even bigger space width and try to repeat this particular experiment or repeat this particular derivation. So, we will get an overall idea.

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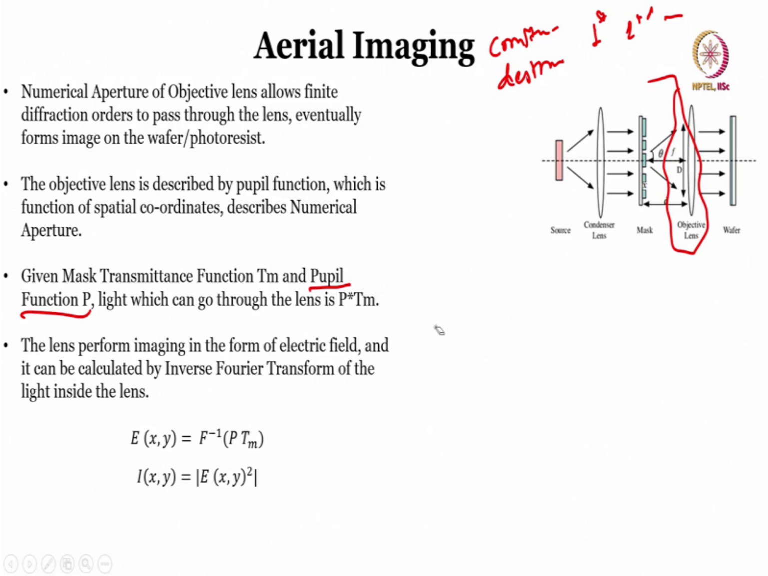
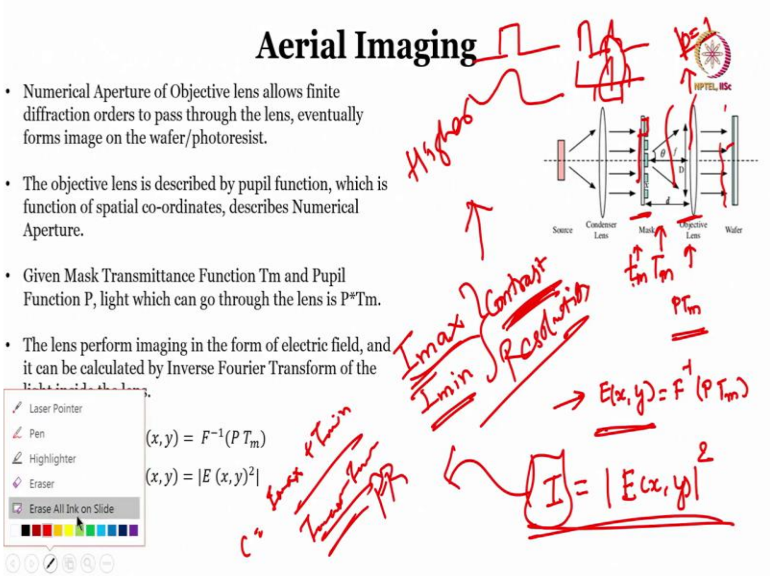


Aerial Imaging

- Numerical Aperture of Objective lens allows finite diffraction orders to pass through the lens, eventually forms image on the wafer/photoresist.
- The objective lens is described by pupil function, which is function of spatial co-ordinates, describes Numerical Aperture.
- Given Mask Transmittance Function Tm and Pupil Function P, light which can go through the lens is P*Tm.
- The lens perform imaging in the form of electric field, and it can be calculated by Inverse Fourier Transform of the light inside the lens.

$$E(x,y) = F^{-1}(P\,T_m)$$

$$I(x,y) = |E(x,y)^2|$$



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$$(x,y) = |E(x,y)^2|$$

We will quickly move ahead. This is called, as I mentioned aerial imaging. So, I have been told you before as well that numerical aperture limits, it allows a particular range of refracted orders. Now, you would have learn in previous your plus 2 classes and all there are constructive and destructive interference. Based on that we get different diffracted order first order, second order, third order which you have seen here in the pattern as well.

So, all this thing you would have seen it, first order, second order, third order and all. So, there are certain orders only can pass through your objective lens. It is like some kind of screening or not all the diffracted order can pass through objective lens and finally contribute to your final images, and how much can we pass through that, which is known by pupil function. So, so far what we had tm, tm is your mask transmittance function, let me right there only, so it would be clear for you.

Let me so, so far what did we have? We have first of all tm, mask transmittance function, what is coming on mask. Then from that we got a diffracted pattern Tm or even specific if I put it that diffraction pattern can be observed here also. And then, this objective lens say I cannot allow all the orders to pass through because I have finite dimension, I have my own function known as pupils function. So, whenever this pupil function is 1 or for those coordinates pupil function is 1, I will pass, allow that order to pass through. So, that is nothing but, see this thing mask transmittance function, this diffracted pattern and here whatever comes is nothing but p into Tm.

So, that is your actual diffracted light which can go through the objective lens which has made through this lens. And further the lens which is performing imaging it is whatever signal is coming is in terms of electric field and finally, the light inside the lens which is coming here it can be identified by (for) inverse Fourier transform earlier we have taken Fourier transform here for diffraction here we are taking inverse Fourier transform to get the final electrical field coming out of that.

Very important to have basics of Fourier transform and inverse Fourier transform if you have any doubt related to that, you can ask us in forum and this is your electric field. Again, light this we are saying see very important you have to mention the light, light is EM waves it can be characterized by electrical and magnetic fields why we are only considering electrical field, magnetic field is perpendicular to that we can identify one field if we have the idea about the another field.

So, this is your electrical field and finally, the thing which matters ultimately is your intensity at one point of time what intensity you are getting. So, that intensity is nothing but the square of your final electric field. So, this is very important what you are getting and this intensity is nothing but it falls onto your wafer on the PR and based on the intensity of this your PR reacts.

Again, based on your mask, you are getting mass transmittance function, you are getting diffracted pattern, you are getting pupils function, you are getting the exact light intensity of the light which is falling here on the wafer and then the important thing is based on the maximum intensity and minimum intensity defines your something called contrast, how this contrast affect final imaging. So, contrast is nothing but how higher intensity it is defined contrast is defined if I am not wrong Imax plus Imin by Imax minus Imin.

So, higher the contrast better it is for you because you are treating your, this region, there will be as you mentioned, if mask function is like this, you are getting this kind of thing, if mass function is repeatative, you are getting different, different orders like this, etcetera. This is an illustration. So, whenever it is opaque you are getting some form of replica of that particular region.

So, this higher intensity means you are getting very high response or high energy light for that it will make it will make the PR soluble in that region or the complementary of that. So, you are getting better faithful reproduction. Again, contrast is another very important parameter along with resolution for any litho process, but contrast is more or less resurrected to optics. So, let us not go into the detail considering, I do not want you people to, get overwhelmed with the different content.

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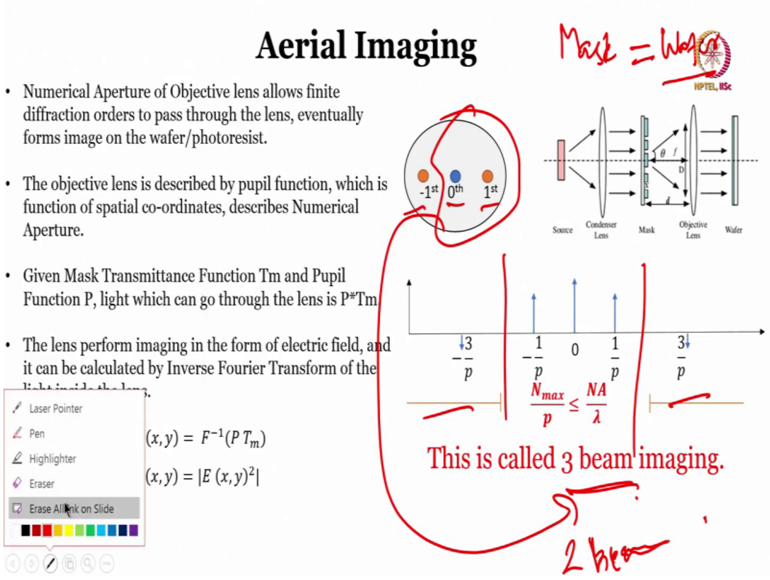

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$(x,y) = F^{-1}(P\,T_m)$

$(x,y) = |E\,(x,y)^2|$

$$\frac{N_{max}}{p} \le \frac{NA}{\lambda}$$

This is called 3 beam imaging.

So, this is like 0 first and all. So, if you put some limit here only if some of them will go through based on the dimension of your lens and the other or whatever diffracted it will get diffracted out and it will not be considered not be a part of final image that is why exact whatever is there in mask will not be exactly same whatever is there on wafer. Pattern on mask will not be exactly same on wafer there. That is why some other correction needs to be done which will be covered in the upcoming slides. So, this is called 3 beam imaging where why because of this thing, only 3 beams are allowed considering that one is 0th order, first 1 and minus 1.

Let us say due to something we are only getting this particular 2 thing that is called to beam imaging, there are pros and cons of 2 beams and 3 beam imaging, 3 beam gives better fidelity but 2 beams gives less dependence here by meaning of 3 beam means, all 3 beams should come to one particular point at exactly same time to get the faithful reproduction of the imaging, whereas in terms of 2 beams, that dependency is later, so 2 beam is better in that case. So, now we will quickly see the enhancement technique, I hope you have a brief idea about how this imaging and all works ultimately helpful for a neural engineering aspects and all this thing.

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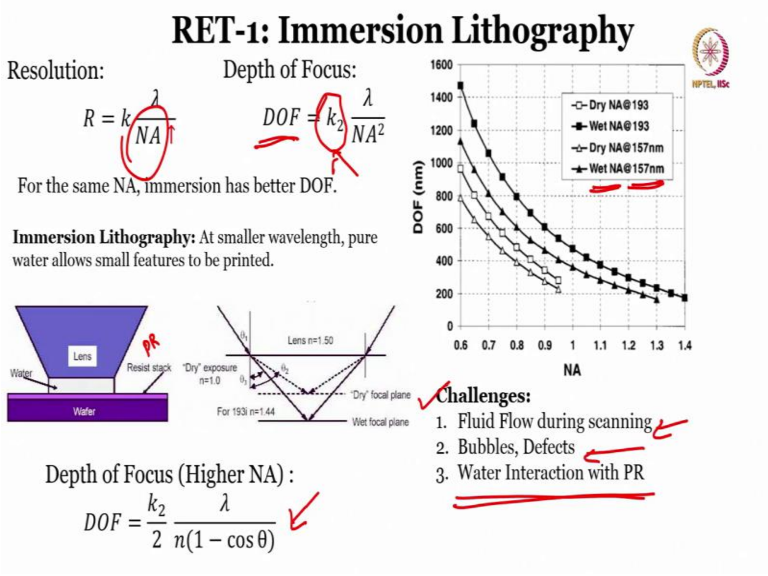

RET-1: Immersion Lithography

Resolution:

$$R = k\frac{\lambda}{NA}$$

Depth of Focus:

$$DOF = k_2\frac{\lambda}{NA^2}$$

For the same NA, immersion has better DOF.

Immersion Lithography: At smaller wavelength, pure water allows small features to be printed.

Depth of Focus (Higher NA) :

$$DOF = \frac{k_2}{2}\frac{\lambda}{n(1-\cos\theta)}$$

Challenges:

1. Fluid Flow during scanning
2. Bubbles, Defects
3. Water Interaction with PR

So, let us quickly see the resolution enhancement technique first one is immersion lithography, you know by changing NA you can improve the resolution at the cost of depth of focus, because when you increase the depth of NA, depth of focus will be reduced. In that case depth of focus will be reduced which means you have a very, very less a precise movement of your objective lens, you cannot put it anywhere you want, less degree of freedom comes at the cost of better resolution. There are studies for that what it does physically is this is your lens, this is your wafer same illustration what it was there here like this lens and then some lights was propagating this is your wafer on which this is a PR and then it falls here.

Same thing is here nothing difference, but just to give you people an idea, this is the wafer and which resist stack which is nothing but your PR. And then there is a water. Earlier what was there? Air. If you replace it the intermediate medium by water you immerse a fluid there, what they say is, see there will be some difference for a one particular nanometer line, what difference how, it will also change the your upcoming settings and that is why depth of focus gets affected.

This is your overall, this is done for one particular PR, photoresist. It is a function of which source you are using, which kind of numerical aperture you are using sometimes dry means only your normal air where its sums of wet means you can put some water and all this thing for the same numerical aperture you are getting immersion getting better depth of focus.

So, why that there will be k2, this is a different system parameter which is involved there I am not going to detail for that. W.hat are the, and as I mentioned, when you go for higher NA, your depth of focus parameter changes, these all are empirical solutions. So cannot be applied in all positions all possibilities, all combinations Based on different, different combinations of your parameters, this parameter changes.

So, for higher NA, this is a formula what are the challenges if you want to go for this particular method is first is instead of air you are putting fluid. So, you have to control the flow and all this thing. With water, if you put the water that comes bubbles, which might result in defects ultimately on the thing, because this is at the in between medium from your lens to wafer in between you are creating a defect, which will affect the light traveling through that particular water and might affect, and finally, there is no air in between and resist stack and there is a water.

So, if there might be some interaction of water with PR. So, that also results in some kind of deformity there are a list of defect which can affect. So, these are the challenges, but the good thing is it is improving NA and that is why we are getting lesser resolution and you see that improving NA has the biggest contribution in improving your overall resolution. So, this is one of the method, you can check it in detail. If you are interested, let us move to the other method.

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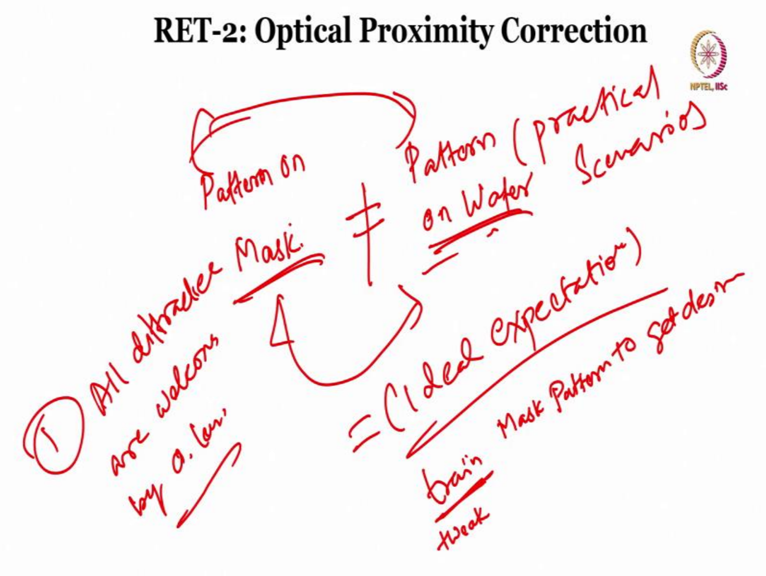

RET-2: Optical Proximity Correction

Which is very important is optical proximity correction. Now I already told you before that pattern on mask is not equal to pattern on wafer, or entire goal of the fabrication is to make this thing equal. But this is like an ideal expectation. And you all know, in real world, ideal thing does not happen. This is the practical scenario. Then why it is not same? One of the reason I told not all diffracted orders are welcomed by objective lens. So, this is one of the reasons there can be plenty of other reasons, but, the main point is the pattern on mask is not the same as pattern on wafer than what to do to make this happen.

What you can do is based on experience, based on your output and input relation you can train again not talking about machine learning, you can train your mask pattern or you can in other words better what is you can tweak your mask pattern to get desired response. What it does is this is your expected pattern on mask not coming on wafer, change the expected better not mask, add some more detail more structures which will result the actual to actual desired pattern on wafer, there are models for this to identify and this is overall optical proximity correction. So, let us just quickly see that.

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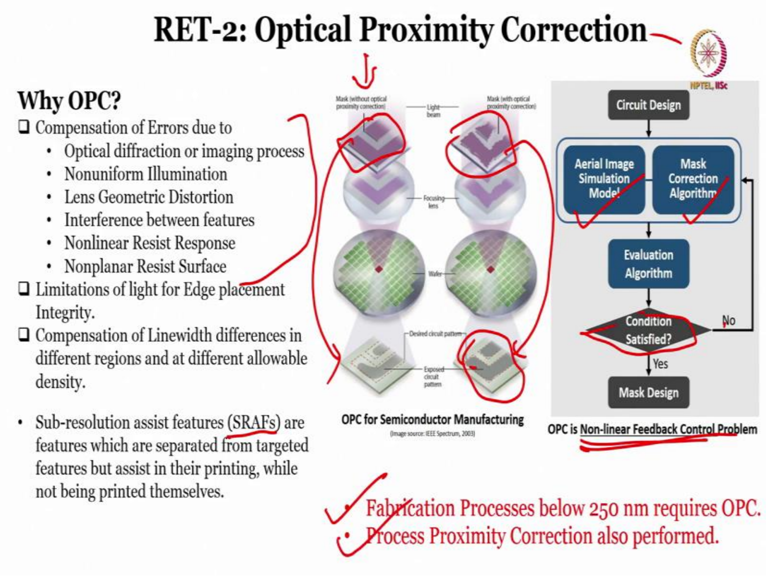

RET-2: Optical Proximity Correction

Why OPC?

- ❑ Compensation of Errors due to
  - Optical diffraction or imaging process
  - Nonuniform Illumination
  - Lens Geometric Distortion
  - Interference between features
  - Nonlinear Resist Response
  - Nonplanar Resist Surface
- ❑ Limitations of light for Edge placement Integrity.
- ❑ Compensation of Linewidth differences in different regions and at different allowable density.

- Sub-resolution assist features (SRAFs) are features which are separated from targeted features but assist in their printing, while not being printed themselves.

OPC for Semiconductor Manufacturing

(Image source: IEEE Spectrum, 2003)

OPC is Non-linear Feedback Control Problem

- Fabrication Processes below 250 nm requires OPC.
- Process Proximity Correction also performed.

So, this is compensation due to diffraction imaging non-imaging this all are reasons, possible reasons, one of them I already told all are possible reason you can explore it limitations of light with edge production compensation of line widths and all that is fine. This is what I want you people to see this is my actual desired mask this pattern I want and what I got here, see this. This can be due to anything and again you can see that this pattern is here you might have to move it to get the desired pattern.

And this is your wafer, and you are here you see that your entire dimension is getting reduced and you are getting the same device and multiple wafer. And finally, you will dice it to get one device which is here. But you are not getting the kind of design you want. I am talking about this particular example, this and this is not matching, you can see that. But then you did some analysis, you have some magic to add and remove some particular aspect and you change your mask from this to this, and then you focus it and try to get it you are getting much better design, you see the mask here and mask here.

Again, this is not matching, but this is what you want, so this is something called optical proximity correction. What it does is, it gives a main shape as it is, but by removing and adding some more segments to that it does that particular thing for that it used some aerial image stimulation model, it uses some mask correct algorithm. And then, it checks your final design, whether it is verified, no, then again, do the same iteration, from circuit design to mask design, it is a nonlinear feedback control problem.

And what you are adding your additional aspects and all that is called s wraps, sub resolution assist features, that are used to get the desired design using this thing. Let us quickly see one more thing, this is like a known fact that below 250 nanometer you use that. And process proximation or correction or correlation also performs that are two other methods also.

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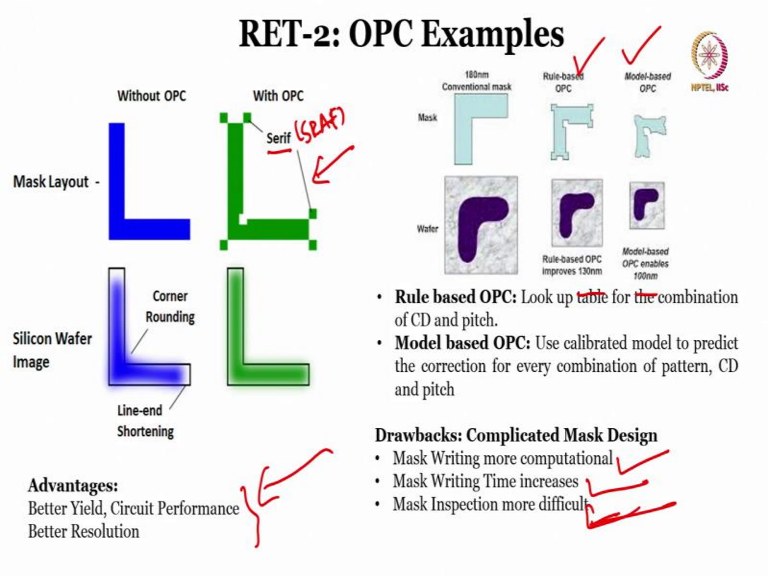

RET-2: OPC Examples

- **Rule based OPC:** Look up ~~table~~ for ~~the~~ combination of CD and pitch.
- **Model based OPC:** Use calibrated model to predict the correction for every combination of pattern, CD and pitch

Drawbacks: Complicated Mask Design

- Mask Writing more computational
- Mask Writing Time increases
- Mask Inspection more difficult

Advantages:
Better Yield, Circuit Performance
Better Resolution

See this thing there is one more example it is really good to develop an understanding this is without OPC you are not getting corner, I know like edges proper, whereas if you add this kind of serif or SRAFs, you see sub assistive resolution enhance features something like that sub assistive resolution, sub resolution assist features. So, this is what you are getting it again at 180 nanometer or below 250 you have to use it, 180 you are getting this, but if you go to 130 or 100 nanometer see your things are getting changed by rules and model based OPC these are algorithms one is based on a lookup table approach. Other one is you use some formulas and consider CD and all this thing and get this particular done.

Now, this is good thing is it is getting better design you can clearly see, better design better performance, because even a slightest change will result in, it might not serve the purpose ultimately because even one transistor fails, it might damage the entire design of your circuit. So, it is a better yield better resolution better circuit preformation comes with all this thing whereas if

I talk about drawbacks, what it does is it is changing your mask, now you are getting you want a better mask, you want a more computation for mask writing, and your mask infection, inspection also should be better.

One thing what we have discussed so far is we have mask and we want generate that particular pattern, how you will get that particular mask. So, there are mask writers available, I would like you people to explore this particular aspect by your end from your end that check what are the mask writing how mask writing happens, but this OPC will make more computational mask writing will result in more time for mask writing will result in more inspection time for mask writing as well all 3 thing comes at the cost of better yield better circuit design better resolution that is why it is being used for fabrication below 250 nanometer.

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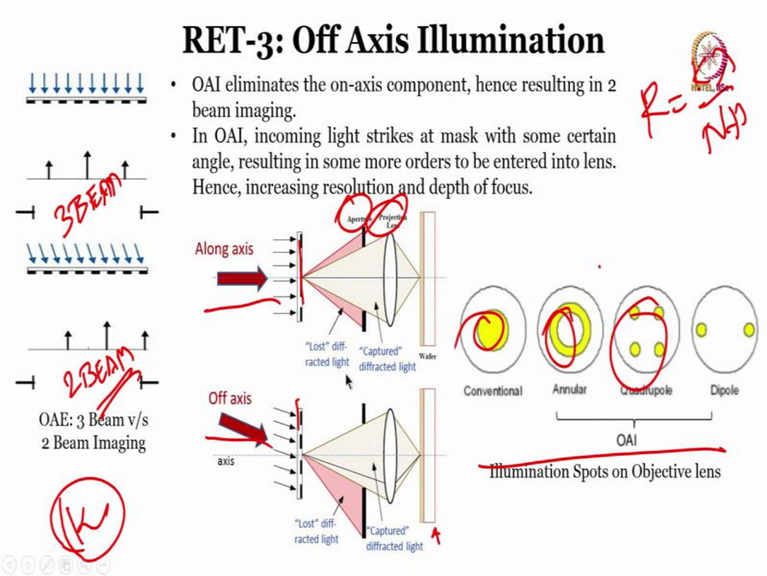

RET-3: Off Axis Illumination

- OAI eliminates the on-axis component, hence resulting in 2 beam imaging.
- In OAI, incoming light strikes at mask with some certain angle, resulting in some more orders to be entered into lens. Hence, increasing resolution and depth of focus.

OAE: 3 Beam v/s 2 Beam Imaging

Illumination Spots on Objective lens

So, let us see one more thing, I already told you off axis illumination that whether light is going along the axis or off axis normal to the mask or at some angle to the mask, when it is normal to the mask you are getting 3 beam, 3 beam when it is oblique it might happen you will only get 2 beams. But this is desirable because it results in somewhat less finer resolution it also changes your system parameter K remember the formula R equal to k lambda by NA. So, when your k changes, you will get a better resolution.

Also, it also depends on how you are giving the light whether it is like this kind of conventional, annular, quadrupole, dipole all these things. So, how you are giving the light at what angle you are giving the light depending on the aperture and projection lens this is the same as your objective lens as well it will decide that which kind of illumination or what kind of pattern you will get on the wafer.

So, this is like I am going slightly faster, but just to give you people an idea about 2 beam and 3 beam improves the k and based on ultimately it will result in the resolution enhancement. We can go into the detail, but it will be slightly it can be a separate TA class altogether. So, this is just to people give you people an idea just want to tell you I will touch upon this topic.

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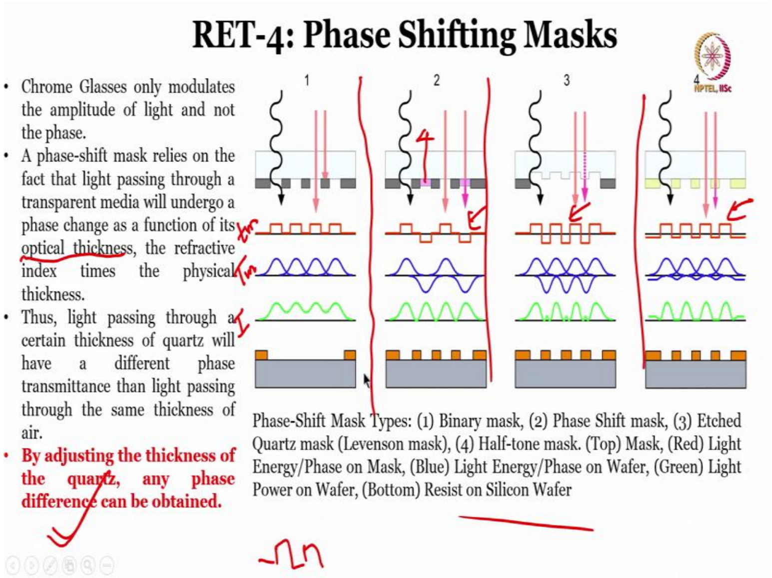

RET-4: Phase Shifting Masks

- Chrome Glasses only modulates the amplitude of light and not the phase.
- A phase-shift mask relies on the fact that light passing through a transparent media will undergo a phase change as a function of its optical thickness, the refractive index times the physical thickness.
- Thus, light passing through a certain thickness of quartz will have a different phase transmittance than light passing through the same thickness of air.
- **By adjusting the thickness of the quartz, any phase difference can be obtained.**

Phase-Shift Mask Types: (1) Binary mask, (2) Phase Shift mask, (3) Etched Quartz mask (Levenson mask), (4) Half-tone mask. (Top) Mask, (Red) Light Energy/Phase on Mask, (Blue) Light Energy/Phase on Wafer, (Green) Light Power on Wafer, (Bottom) Resist on Silicon Wafer

Also, another thing is your face shifting mask. It is also very important this is again your mask transmittance function, your mask transmittance function, then your overall diffracted pattern and this is your finally intensity. So, this thing decides that, first point is binary mask what we have discussed so far. At that time, I told you I will explain mask transmittance that whether it will be only 0 and 1 or something else. If it is something else, it is called some different mask or, whether you are trying to you see this thing here it is 1 0 and minus 1, how this minus 1 is achieved? By putting this pink color thing.

What is this pink color thing? Pink color thing is nothing but your chrome glass, it modulates the amplitude and light, it modulates the face of the light as well. And by changing the width of this you can get a desired, mask or desire mask transmittance function. See all these four thing if you see 1 2 3 and 4 all this thing which is changing is the mask transmittance function basically shifting the face of the mask if I say a minus 1 it is shifting the face of the mask. It realized through on the fact that light passing through a transparent media will undergo a phase change as a function of its optical thickness.

The refractive index times physical thickness. So, this is again a formula for that calculation for that, but the main part is this funda remains this, by adjusting the thickness of the quartz, quartz is nothing but the pink part which you can see here, any phase difference can be obtained and based on that you can get a desired pattern.

You see this is the same thing this is the same thing, but here you are getting the final resolution, by just putting this thing here they have edged off some particular part. So, that is called edge pass masks or based on the scientists Levinson's mask and then also you can see different mass transmitter function, different deflected pattern and you get a desired response.

So, and as I mentioned, there are different things that, this top one which is a red part, it is the mass transmittance function, energy on mask, then blue part is energy on the wafer and then finally the intensity and whatever is coming on resistor if you can see that. So, this is like a another very important aspect of phase shifting mask, you can get the desired pattern. I would like you to explore in little more detail to get more idea.

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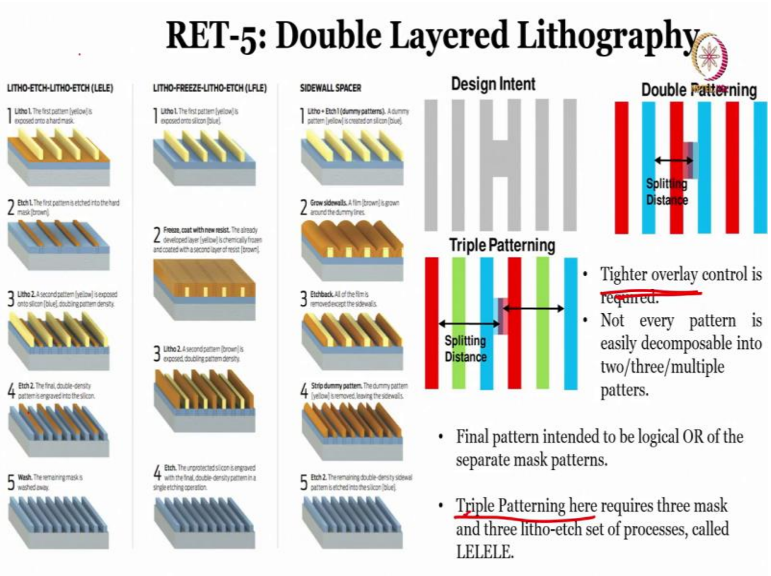

RET-5: Double Layered Lithography

- Tighter overlay control is required.
- Not every pattern is easily decomposable into two/three/multiple patters.
- Final pattern intended to be logical OR of the separate mask patterns.
- Triple Patterning here requires three mask and three litho-etch set of processes, called LELELE.

And the finally double layer lithography instead of doing it once you just remove the mask it once and do this. There are different, variants of that if you do it 2 times, that is a double layer lithography, if you do it 3 times that is LELELE, but this all comes with, you have to take care of this overlay which is here. So, this all final pattern would be logical OR of all 3 patterns what you can see here. Again, sidewall spacer is another technique, litho freeze litho edge and you can do triple patterning also.

And but the thing is, there are challenges as I mentioned, your overlay should be tighter, and not every point pattern, let us say if you are talking about MOSFET and or not every pattern can be decomposed into 2, 3, 4 patterns. So, for those complex designs, you need to think about some alternatives, what are the alternatives. Some of the previously discussed technique might be applied and also there can be possibility use some different form of lithography we are saying optical lithography, or this projection lithography.

There are some different EUV lithography and all where, we have more we are getting more resolution and all. So, this is just again to give you people an idea enable you to think about how to travel from micro to nanometer and what are the techniques being used. So, you can explore each with a whichever technique you want in detail at your own.

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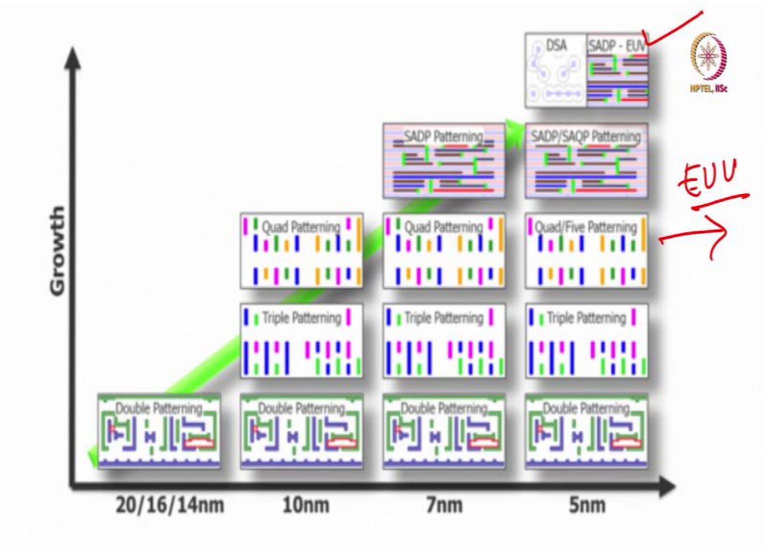

So, finally, this is the growth in terms of VLSI or getting micro electrode arrays or even nano electrode arrays if required from few nanometers to micrometers all this resolution enhancement techniques can be used, you have to be very smart, see, here they are started using EUV when they go from 5 nanometer even if you go further there might be EUV and some other techniques.

So, what you can do is you can based on your application, you can decide your process flow, and you can decide which kind of litho technique you want to use and how to tweak the parameters and litho optics to get an overall idea.

So, this is what the just of this tooling series, which I would like you people to explain and realize that how we are transferring from micrometers to nanometers in order to get different nano structures. So, this is like an overall idea. I hope it is clear, it is slightly difficult to going through in each one of them detail as I mentioned, in each resolution enhancement technique itself is a one class or even we can take a short course on that.

But for you people to understand and, the agenda to let you people swim by yourself when it comes to this kind of technique. So, I hope it is clear now, you can explore by yourself and if you have any doubt in that process, feel free to write us in forum. I will see you in another TA session, and lab session as well. Take care bye.