Biomedical Ultrasound: Fundamentals of Imaging and Micromachined Transducers

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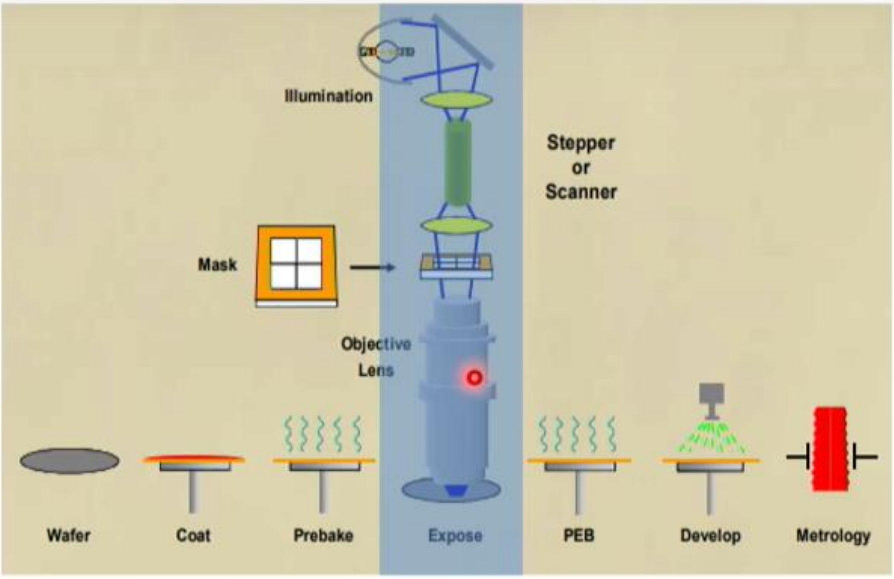
Lecture: 30

Lithography optics II

Hello everyone, welcome to this course and continuation module on lithography optics. In today's class we will see some of the techniques about resolution enhancement and also, we will see how the light travelling from your illumination source through all the condenser lenses and followed by mask and objective lens before it finally gets printed on your wafer. So, for today's thing prior to and we also understand how mathematically it is modeled right. So, in the previous class I was informed that diffraction limited imaging. The entire you know kind of all beams coming throughout all this structure ultimately falling into the wafer that is finally light is being calculated or PR solubility will get changed because of a particular process known as diffraction-based lithography or this interference. So, how do we mathematically approximate that we will see that in today's class also as I mentioned previously that all the semiconductor industries mainly depend on the parameter known as resolution.

So, how that resolution gets enhanced or how you are getting smaller and smaller devices right if you remember I informed about Moore's law. that how Moore's law is being maintained or currently it is like more than Moore we are in the era of more than Moore where we have to think about something else. But before that prior that how for 3 to 4 decades we can maintain that particular rate of miniaturization all this thing we have discussed. Additionally, I have given a glimpse about the course that what were the important topics have been covered or will be covered.



Lithography Sequence

Also, we have followed a top-down approach to understand about you know what as the most like how fabrication or micro machining are important than we have seen in particular fabrication. What were the unit processes, which processes are important in fabrication. Also, we have seen that in that important process, what are the sub-processes. So, for those who have kind of attended last class would be aware that fabrication has thin frame deposition, lithography and etching, these are like you know some of the main techniques, there can be sub techniques into that and like thin film deposition as PVD, CVD, in PVD you will get sputtering, e-beam, thermally operation, in CVD you have LPCED and some other variants as well. So, as you know we have seen all this sub process and processing in glimpse and throughout the course we have been discussing this process and application with different process flow.

Then we discussed that lithography is important, in lithography what are the important sub processes. or which is the most important sub process prior to knowing or identifying or assessing which is the known sub process we should know what the sub processes are. So, we have seen that PR coating, photolysis coating, if required some form of wafer preparation, PR coating, pre bake, exposure, post exposure bake and development followed by characterization. These were some of the sub-processes. In those particular sub-processes, which is the most important thing that we have seen.

Additionally, we have gone through multiple numericals so that I believe you know we have now developed an understanding of how to if spin speed is given how the thickness on the top of wafer of thickness of PR can be altered. We should know if a particular pitch is provided for a given photolithography system whether we can reproduce those pitch and numbers using that system or not. So, this kind of numericals I have covered not only numericals I have also shown some of the additional information which is very useful. For example, we have seen that energy spectra how G line, H line, I line or even further you know excimer lasers like argon fluoride and kipton fluoride lasers have been used what is the wavelength. in which particular range it lies whether it is visible range, or you know UV or what kind of range it is all this thing we have covered.

Today we will definitely develop upon that, and we will see the mathematical modeling of optics and resolution enhancement techniques. Another important point I have also shown about SU at photoresist data and numbers like every IC right comes with its own data sheet. same way each and every PR comes with its own data sheets. So I have shown you the number and encourage you to go through the entire data sheet of different photo resistors which I hope all of you have gone through okay. So before we start today's class we will see a quick recap of what we have seen before So this is our overall you know thing the most important point or most important drawing is this one that we have seen this is a lithography process and as I mentioned condenser lens will be here mask and objective lens let me just put a laser pointer so it will be easy for you yeah so this would be your condenser lens this would be your mask followed by objective lens I mentioned earlier that condenser lens and objective lens is for the sake of simplicity when I say condenser lens it cannot be only one lens there will be multiple lenses okay same goes for objective lens as well mask design, mask loader all this thing.

So, this was our fundamental diagram to simplify simplified diagram to understand how lithography process works okay. Further this was a quick question that which kind of exposure is this of course as I mentioned it depends on diffraction also depends on the projection and all and it is called projection printing. I have mentioned about reinventing the wheel right for any particular science you should know how the flow is how it has been reinvented from scratch. So earlier it was contact printing then I told you that if this is your mask and you want to print this on your wafer you can do it for minimum number of time then your mask gets deteriorated when your mask gets deteriorated you would not be able to get the same print.

And as a result of that contact printing stop then it comes to proximity printing which has its own limitation of resolution of 4 micrometer whereas I also request all of you to check what nanometer technology your particular smartphone uses. right, it would be in some nanometer. So, considering that this project proximity printing limit of 4 micrometer is not proper. So then further we went a step ahead or you know scientists have gone to a one step ahead and made a projection printing out of it. So, that is also like an important some small point but important point.

Further I have also explained about the resolution formula I mentioned at that time it is an empirical formula which has been added after observations that resolution depends on three things right. One of them is system parameter, second one is wavelength and third one is numerical aperture. Now I have explained about if your light is getting incident in a normal manner, this is your mask, this is your lights, if it is in normal manner then means 90-degree angle ideally, if it is in normal manner then the K value would be 0.5. If it is in oblique incidence the K value would be 0.25 okay based on that your resolution would be calculated that is what we have seen about the K value. Further we have seen about the wavelength lambda so lower the wavelength better it would be if we think about this formula as a mathematical formula.

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

$$R = smallest\ half\ pitch\ that\ can\ be\ printed$$

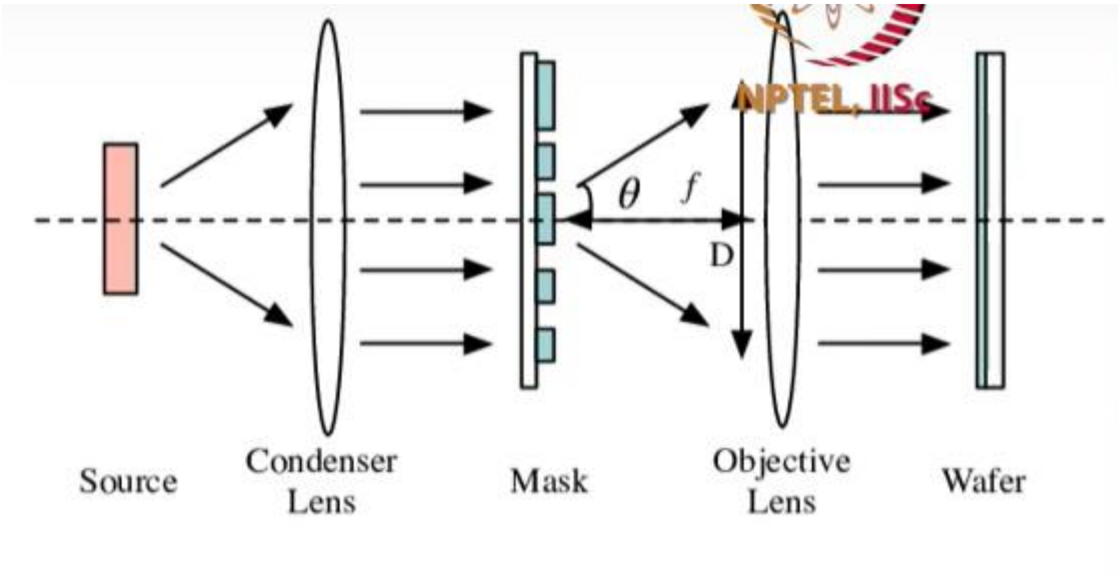
$$k_1 = system\ parameter$$

$$\lambda = wavelength$$

$$NA = numerical\ aperture$$

However, when you decrease the wavelength, I mentioned that it these are EM waves light propagates through your source reaches that a wafer EM waves they have their own relationship between the wavelength and the energy of thing energy of a particular wave or beam. So, and also, we have to consider medium and also considering that we have to very cautiously So, that was another point also numerical aperture is what we have discussed numerical aperture is an ability of a lens to acquire light. So, generally it comes into the consideration for objective lens when your lights are getting diffracted at a higher and higher angle and gets deviated in the other side that time, we might not be able to capture the entire light.

There as a result of that we might let you know some of the diffracted light might get lost and hence that is where numerical aperture comes into the picture, we saw it quickly last time so we will discuss it a little bit more on that as well. Further this is like a diagram. What I like about this is I mentioned that if you see here in the lithography sub process starts from illumination, mask, exposure, objective lens and finally the wafer. See illumination, condenser lenses, mask, objective lenses and your exposure. Same way this is like this okay illumination. Your condenser lens, mask, objective lens and wafer flow wise top to bottom.

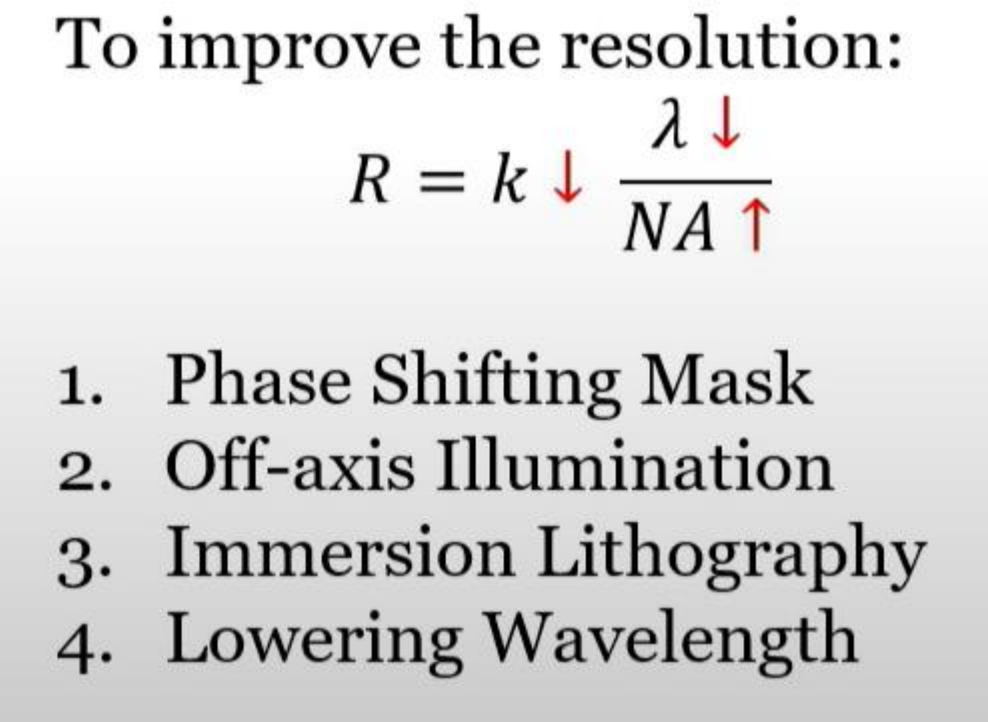


You keep the same thing rotate it by this and keep it like this okay. In that case if you see this is your source condenser lens, mask, objective lens and wafer okay so same thing what we have seen it is a simplified diagram for that this is a diffraction limited imaging okay I already mentioned that entire overall imaging depends on your diffraction phenomena okay. Furthermore, we have seen what depth of focus is so I explained the ability of you know that light or ability of this particular lens you can see here let me just So, if you can see here the ability of this objective lens lenses are placed strategically at a very precise location. So, how much tolerance you can allow for your objective lens or lenses that is what your depth of focus now the higher the value of depth of focus it is better for you because you will get a chance to place it here and then little bit precise placement comes with its own challenges and cost. So, we have to consider all these parameters. Also mentioned that numerical aperture higher the better but it will also affect the depth of focus.

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

So that is another point we must make a trade off out of it to design and get a proper resolution we have seen that. Further I have mentioned that if you just think about the formula mathematically then what are the how can you improve the resolution. So, there are multiple techniques for that I have briefly named it at the end of last class these are the techniques, and it affects the several parameters like as I mentioned if you have a phase shifting mask. Here generally you see what we have learnt is in the if I can just one minute, I will put a laser pointer again yeah. So, if you can see it here, some of the lights go through, others get diffracted and reach here.

Generally, we do not consider a mask as a material that can change the phase of the light. Generally, we consider it can either get some diffraction, it allows some diffraction, or it will either in a very simple term, either it will block the light, or it will allow the light. In a way, either it will completely absorb or completely stop the light, or it is allowed, so it will just affect the amplitude of the light. Okay, but however if you use a certain material if it changes the phase also it is called phase changing mask. So, there are some applications for that as well we will see that off axis illumination, I have already mentioned that currently this is a normal incident I told you right.



To improve the resolution:

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

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

So, if you see here this is a normal incident to your mask this degree is 90 degrees. So if this is normal incidence you have to you know you will get some value of k your system parameter if there is something else if there is some different form like you will do some and that magic will happen from this beginning source okay keep it in some different position you will get instead of this you will get this kind of thing. So then whenever it collides it collides with a certain angle right not 90 degrees. So that is called oblique illumination and as a result of that you will get some different type of beams reaching to your wafer it is a 2-beam imaging, I have discussed briefly about 3 beam and 2 beam imaging as well. So, that is another point further we have also seen how resolution has improved over the years right.

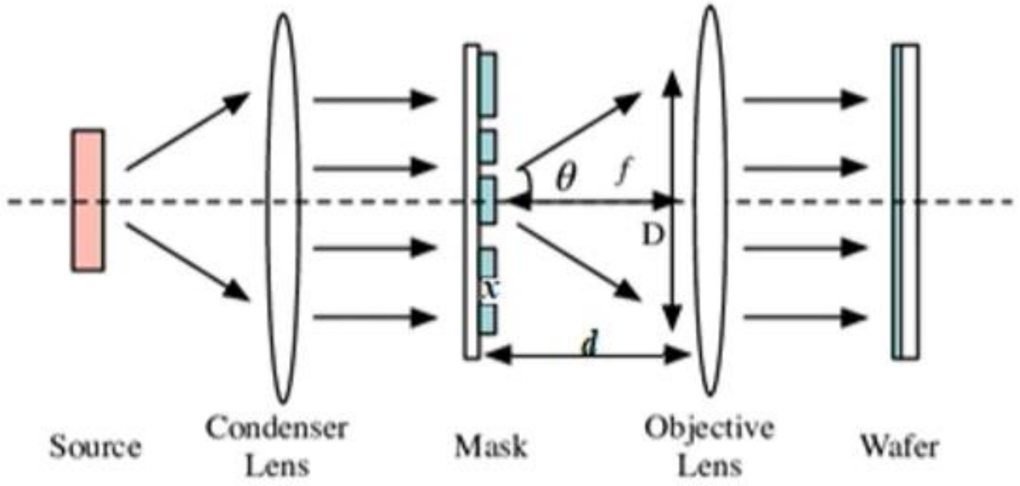
So, I have taken I believe two instances and we have seen how it has improved due to which particular parameters. So, this is just a summary of that if you can see the screen in

1975 this is particular values were there for system parameter wavelength and numerical aperture. Whereas in 2010 it has been improved to this portion now because of which factor how much it is improved already discussed okay. One very last and important point I have given at the end of lecture is some scenario that consider this photolithography system is used. Consider that this kind of illumination is being used for this particular wavelength and best possible numerical aperture.

So, what was the limit for the lithography resolution for the given scenario. So, if you are watching this video, I would like to pause it and if you have not calculated please calculate it. So, that is like overall quick recap of what we have seen it is like an alaap before any song right that will take you to the song.

So, now let us begin today's lecture. This is a Fraunhofer diffraction. So, there were two types of diffraction which we have studied in plus 2 one is Fresnel diffraction other one is Fraunhofer diffraction.

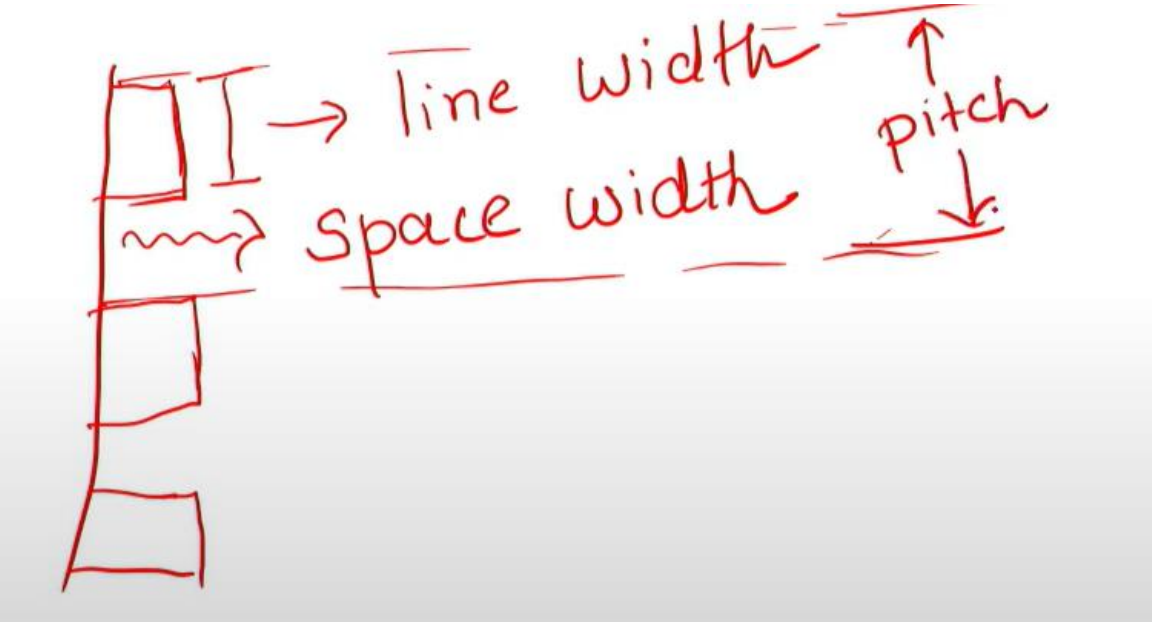
Now what type of diffraction will be applicable in this scenario and why you should know okay let us see that. So, this is diffraction as you already know bending of a light it passes through the slits or edge okay. Whenever there is a enough gap is that it will you know easily pass through but when there is a slit. Slit here means there is some change or some form of edge or some slope or something like that in your mask right when there is an inconsistency or some shape in your mask it will get defected and that is exactly what we want. that your desired design or your mass design should get reflected in wafer.



So, that is possible with your bending of light, but only one lens is not enough because it will bend the light or diffract the light than what you have to collect that light also. So, there should be a complementary lens placed and that is when the pair of condenser lenses and objective lenses comes into the picture. So, this is like your diffraction definition considering boundary condition this is a flow which we already seen. So, there are two types of diffraction as I mentioned one is Fresnel diffraction other one is Fraunhofer diffraction. So, in this case what kind of diffraction would be applicable before seeing that I will just explain this X is hidden here in this space width here.

$$\left.\begin{array}{l} x \approx d \Rightarrow \textit{Fresnel Diffraction} \\ x << d \Rightarrow \textit{Fraunhofer Diffraction} \end{array}\right\} \textbf{Function of wavelength also}$$

Okay, this is your X, whereas this is your distance between your mask and objective lens. So, now you see the overall formula or kind of criteria to decide which particular diffraction method is possible in this case, one is when your x, your x is the distance this is by the way this is called a space width. So, if I can just quickly you know anyways, we will be discussing in greater detail in future, but I am just drawing this line here and let us say this is your design in your mask. We will see this in detail in this class only then there is some space again there is some design and again there is some design. Now it is almost considered this is an equal thing okay so this particular thing where your design is there is called line width okay this is your line width whereas this thing okay which is there is a gap right so that is known as space width.

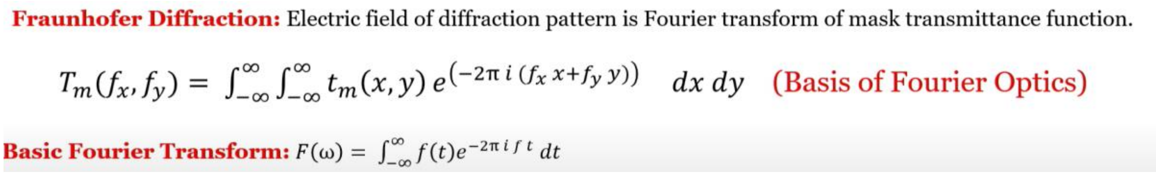


If you are discussing anything related to lithography or this kind of imaging these are very known terminology line width and space width and finally if I take from this line let us, say it is getting here and this is getting stopped here okay. So, this distance of whatever you are seeing here okay is nothing but your pitch okay. So, what you are getting using regular resolution formula is half of this half pitch. So, this is terminology why I explained all this thing here is let us consider if I say now that let us consider X as your space width then all of you will now understand that what do I mean by space width again line when the line is there space where nothing is there and summation of that is your pitch.

So, let me just erase it. So that is your line width and space width in this scenario your space width is X whereas the distance between lens and mask is small d. So again, I want you all of you to stop the video and check which particular criteria is applicable here okay. which particular criteria is applicable here in this case. So, the thing is if you have seen this is a micro nanofabrication what we are talking about. So, your device dimension will be in micro or nanometer range.

Additionally, I hope or like some of you have at least searched or Googled about the photolithography system. If you do that if not please do if you do that you will get an idea that photolithography system is almost of the height of a human being or even more than that and they will put it in a such a way that in front of you there will be a screen okay GUI where you can operate and you know identify and you know tune the parameters. So, considering that the distance between your mask and objective lens would be at least few hundred of centimeter. In contrast to this particular design which is there on your mask which is like a small x which is in micro and nanometer range. Hence, this Fraunhofer diffraction criteria will get specified or will be satisfied.

In that case, we have to apply Fraunhofer diffraction and then Fraunhofer diffraction has its own rules. optics will come into the picture. So, what is that basically see main thing is our agenda is to identify that how this diffracted light goes and how we can quantify it or model it here after it leaves the mask okay. So, this is the formula for Fraunhofer diffraction that electric field of diffraction pattern is Fourier transform of mass transmittance function. Another very important point here as I mentioned this light is electromagnetic wave.



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

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

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

So, if you want to model it you can easily consider your electrical field and then you will get a magnetic field which will be perpendicular to that right. So, this is the basic point of that. So, see the form of electric field of diffraction diffracted pattern is Fourier transform of mass transmittance function. Now why electric field is important because electric field will give you ultimately the intensity. Now another point ultimately what we want is that whatever is there in mass should get reflected on the wafer.

We based on the design of the mask what we are getting on the wafer it should have two different solubilities and that solubility can be changed by calculating the intensity of the light and that intensity can be calculated by considering the electric field which is what we are checking it here. So electric field can be calculated by the Fourier transform of mass transmittance function. Generally, what we have studied so far is a function that can change one domain into another domain. Majorly, when we are dealing with time domain signal, we convert the Fourier signal, time domain signal into frequency domain.

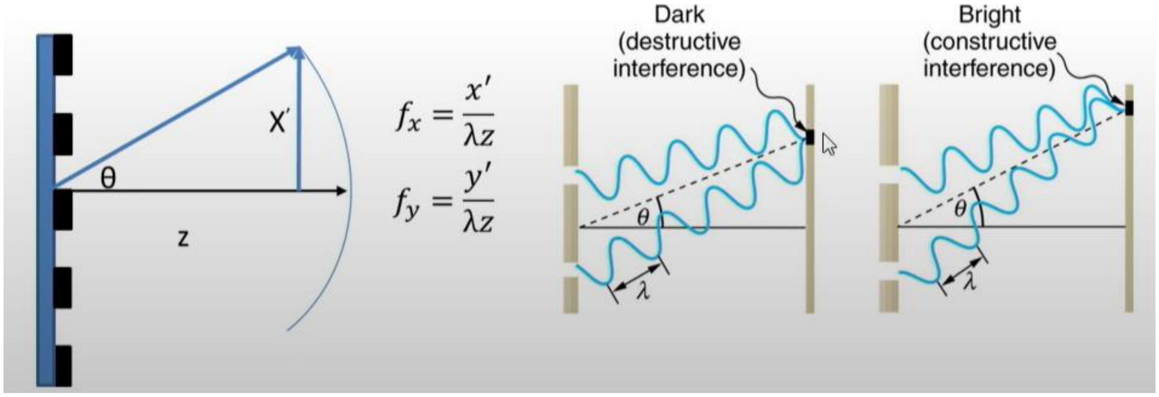
And there are some properties of Fourier transform which all of you should know like what duality property is the time limited signal will have an infinite frequency component if I talk about band limited signal which will have a finite you know time domain infinite time domain that simply if you consider one sine wave. of one frequency only it has only one component in frequency domain but when you plot it into time domain it is you know expanded or it is extended towards both sides towards infinity. On the other case if you are talking about any small square wave or something when you draw a frequency response of that you will get a sinc function, sinc function is again as I mentioned extended for both sides in frequency domain okay. So, these are like basic things or fundamentals about Fourier transform which you should know. Coming back to lithography, this is your electric field of diffraction pattern is Fourier transform of your mass transmittance function.

I want you to analyze both the equations. Let us say this is your equation number 1 and this is your equation number 2. Analyze both the equations and see what the similarities are, what are the differences. Again, as I mentioned for resolution when we thought how we can improve we just thought mathematically just think about this from a mathematical perspective and what do you observe. So, here are the observations that this is easy one first of all this is easy one which is like a single integral some signal is their f of t and then you are getting your transform f of omega it can be omega it can be f like angular frequency or linear frequency.

So, this is yours, this is easy one to understand. So, I started with that, and it is single time integration. So, whereas in this case there are double integration limits remain almost the same. Now we easily understand like you know okay there is a time domain signal we know what is happening okay there is some time domain signal in this case what is Tm that should be the first question okay. So, what is Tm and also in frequency domain or in the simple Fourier transform formula there was F which is your frequency now what is Fx and Fy. So, those are your scaled coordinate or spatial frequency it is defined with a particular you know settings.

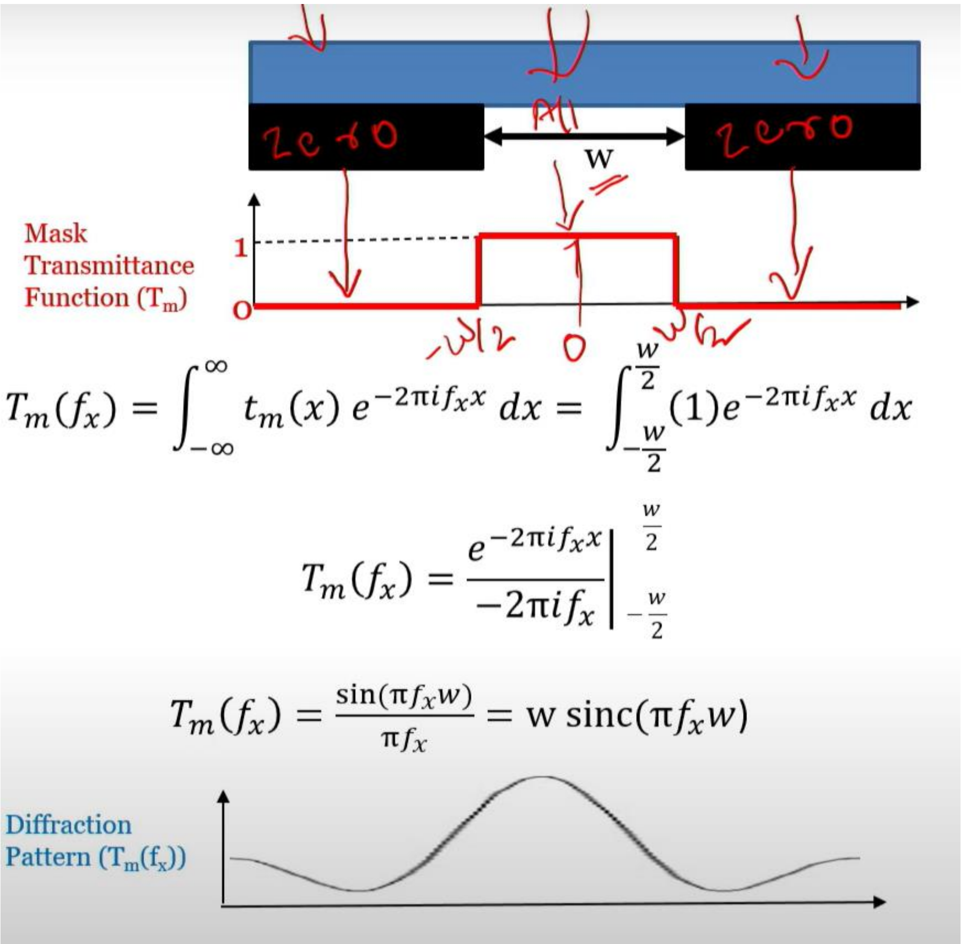
So, before we see how they are scaled coordinates and how it is calculated let me just erase this. So, you see this particular thing, this is your mask, this is your mask which is shown in black, prior to that this is loader okay, it gets diffracted by a certain angle theta for those particular case where it gets diffracted you will get this kind of value. Now X prime is here, Z is here, Z is the distance between your lens and mask whereas X prime is nothing but your how much it is elevated towards the upside. Now Y dash is here but not shown here because it is inside the screen okay it is a 3 dimensional and this is just to brush up the basics that what do you mean by destructive or constructive interference. This entire game depends on how much optical path difference is there in terms of your lambda.

So, if it is like you know n lambda or you know with full cycle you will get a very nice constructive interference, you will get a bright spot there. Bright spot means most of the beams are getting localized that you will get a good energy there okay whereas if there is a like a destructive interference you will get a dark spot okay and you will not get any form of light reaching to that particular point okay. So let us quickly take a couple of examples to have an idea. So, this is your mass transmittance function okay I explained I have like you briefly talk about mass transmittance function it is very easy just see here. Here the light okay is coming from here it is a small let us say one from here one from here okay.



And it is getting blocked now depending on your mask either it will get blocked, or it will get passed through consider that black region currently is blocking your light. So here there is no light coming out from this portion how much light is coming there is no light coming 0 light same as here also 0 light passing through whereas in this case you will get all the lights passing through right. So, this mapped mass transmittance function is the mapped quantification of how much light can pass through the mask. So, you see as I mentioned there is no light that can pass through here, so you will get all values 0, same goes for here as well, whereas here full light is getting pass through, so you will get 1. So, this is an example, I hope now it is clear what mass transmittance function is.

Okay, once you have a value of mass transmittance function you just have to put it into this integral and calculate what kind of diffraction pattern you will have and plot it so you will get an idea okay let us see that. So, this is your mass transmittance function, you know the value right everywhere else it is you know 0. Another important point here we have mentioned is W okay now what is W line width or space width, pause it and think it and tell it is a space width okay. So, this W so we need your final pattern in terms of value of W. So let us calculate it again this is a mathematical derivation it is nothing but a normal integral okay.

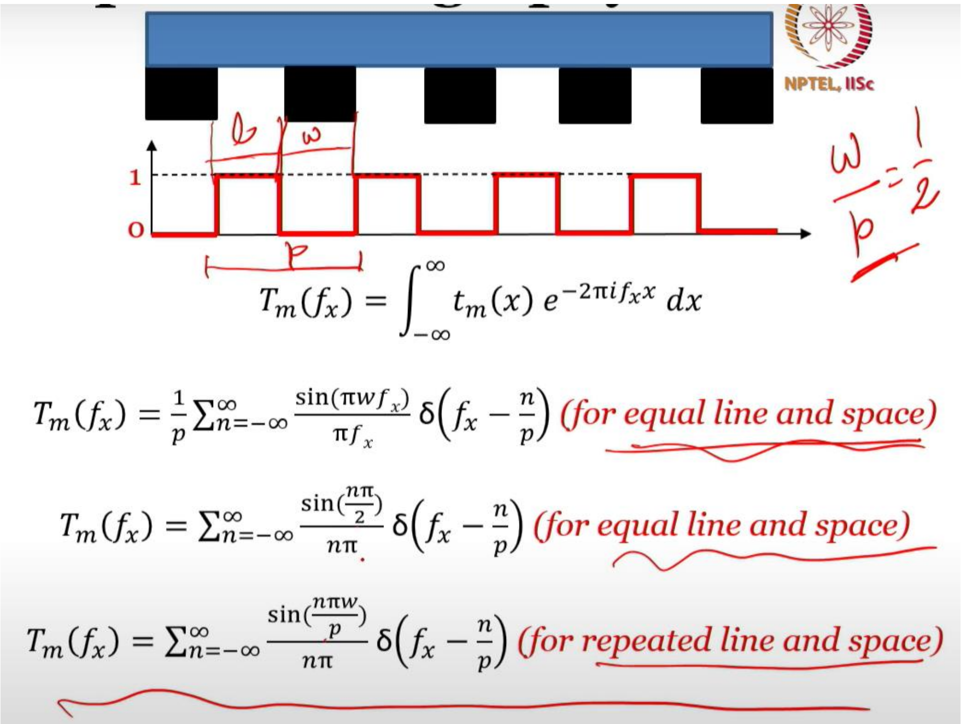


$$T_m(f_x) = \int_{-\infty}^{\infty} t_m(x)\, e^{-2\pi i f_x x}\, dx = \int_{-\frac{w}{2}}^{\frac{w}{2}} (1)\, e^{-2\pi i f_x x}\, dx$$

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

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

So, it is sound you know again it is for the sake of simplicity we are showing it for one dimension. Just to get an idea, further you have to you know kind of superimpose several dimensions thing and also calculate, just put a value 1 here, now this width is W which is your space width right, so take it make a system or you know shift the origin or understand it from here, this is your 0, so this can be your minus W by 2 and this can be your W by 2. So, with that limit you apply the value put the value and calculate the integral you will get this kind of diffracted pattern. So, this pattern is coming out of the mask that is again a sinc function right. So, I mentioned time domain square wave, or you know one pulse frequency domain sinc function and vice versa.



$$\frac{w}{p} = \frac{1}{2}$$

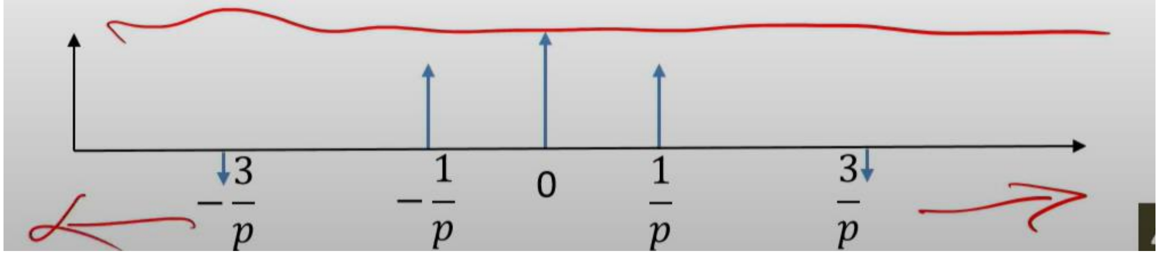
$$T_m(f_x) = \int_{-\infty}^{\infty} t_m(x)\, e^{-2\pi i f_x x}\, dx$$

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

So, you will get this kind of sinc function but how it will look like right how finally the value or you know finally the diffracted pattern will look like considering this as your mask. So, it will be something like this again ideally sinc function is extended both sides towards infinity but not everything we will capture because your objective lens has a finite duration, I will come to that, but this is clear it is very simple right. Here we have taken only one instance where two-line width and one space width is there let us see one more quickly one example. Here we are having a repeated line width and space width so in this if you calculate the value and put it you will get this kind of thing do not get overwhelmed by the formula one by one we will see first we will take this case of deflected pattern you see it is written repeated line and space okay whereas here it is written equal line and space it seems like it is equal line and space if what we have seen previously this is your line width okay and this is your space width it almost look equal this is your W let us say this is line width we will just name it L we will not be using it though and this is your P. Now when equal line width and space width are there your W which is your space width by P will become 1 by 2 pitch is nothing but line width plus space width, when it is equal it will be like this. So, this is your overall formula, I will share the link of this how it is derived, we will not go too much into detail in the mathematical derivation, but this is how it has been calculated. Now, if there is a equal line width and space width in both the cases, you see this W by 2 will get replaced by pi by 2. W by 2 sorry we will get change by P by 1 by 2 okay just put a value W by P 1 by 2 n pi remains as it is okay. So, this is again a derivation now the important point is here, here you are seeing a single function okay when there is only one space width.

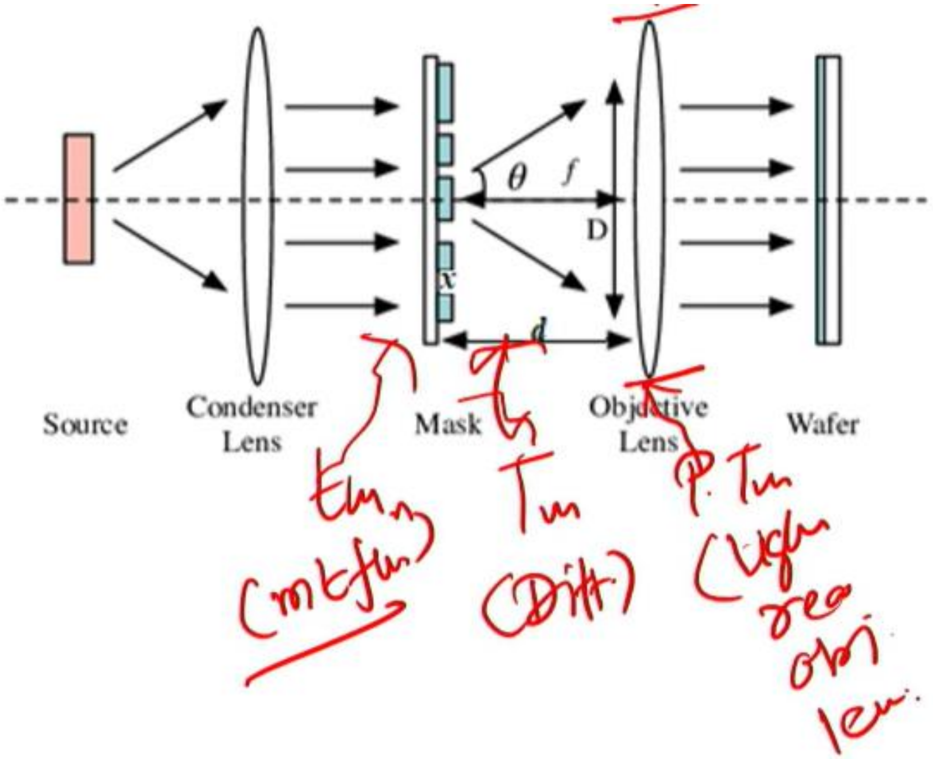


In this case you are getting a result from multiple beams because you see there will be if I draw little bit lighter coming from here okay might get diffracted here and reach to this point. Same goes from here also sometimes it gets diffracted and reach this point. So, all these sinc functions there will be repeated sinc functions will nullify its secondary and side lobes. And you will get this kind of impulses so this would be your diffracted pattern again it is important to see that it will you will get diffracted pattern here also here also. How many numbers of these impulses will pass through the lens decided by your objective lens so how do we calculate that will come to that depends on aerial imaging.

You can find the solution here of the previous derivation. This is an important point that numerical aperture of the objective lens allows finite diffraction order to pass through the lens. You see here it gets diffracted not everything every light or every order get pass through. So, it will get decided by how many orders will get pass through the lens eventually forming an image on photo resist it is clear. Whatever orders have actually reached to objective lens that only plays a role in deciding that how my final image would be look like and hence always whatever you have decided on your mask will not completely get reflected and you will get a shape here.

The objective lens is described by pupil function. Another important property, very important property when it comes to lens is your pupil function. Pupil function will decide that how much light you can pass through, right, which is a function of spatial coordinates and describes numerical aperture. Already I have discussed fundamentally or conceptually what is numerical aperture. The pupil function is a derivation of that particular thing, okay.

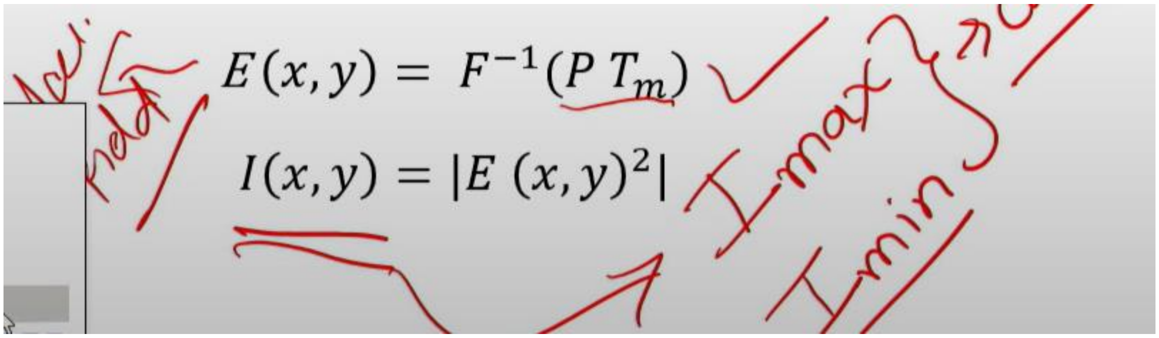
Given the mass transmittance function, here it should be a small Tm, okay. and then you will get a diffracted light which is your see I will tell you easily this is your mass transmittance function then it will get diffracted you will get this then whatever pass through and reach here will reach here okay. This is mathematical like you know quantification or modeling of that if you have a mass transmission function Tm pupils function P then how much light will go through this after letting us say this is your mass transmittance function. Okay, this is your diffracted light, and this is your final lights coming out of objective lens or light reaching you see that okay. Light gets reaching to objective lens okay and further it gets diffracted and then we can model it, so this is for this particular point this is for this diffracted thing here and this is here okay easy. So, the thing is when you given this particular thing how much diffracted light will reach to your objective lens gets decided by P into Tm.



P is just simply if I say it is an enabled P in or something like you know this based on the dimension this much light will pass through. So, this is getting you know decided by P. and what light is coming input light or diffracted light is capital T into M. So, this is light this is what you know the lights what we are getting here and further this is this objective lens performs imaging in the form of electric field and it can be calculated see I already told that how mask or lights get diffracted can be explained in the form of Fourier transform. But then another property how it is getting diffracted but when you put a lens you can calculate you know final light by taking inverse Fourier transform in a way completing the cycle here it is F okay your Fourier transform.

Whereas here you can say that Fourier inverse so ultimately mathematically also whatever you had here in mask you should get it here with some changes that is dependent on your numerical aperture or pupil function. So now if you see this formula, you should be able to understand that I explained here how much light is reaching to your objective lens P into Tm. Now property is there for objective lens that it will make you know the output light from objective lens is inverse Fourier transform it is modelled like that. So that is your electric field.

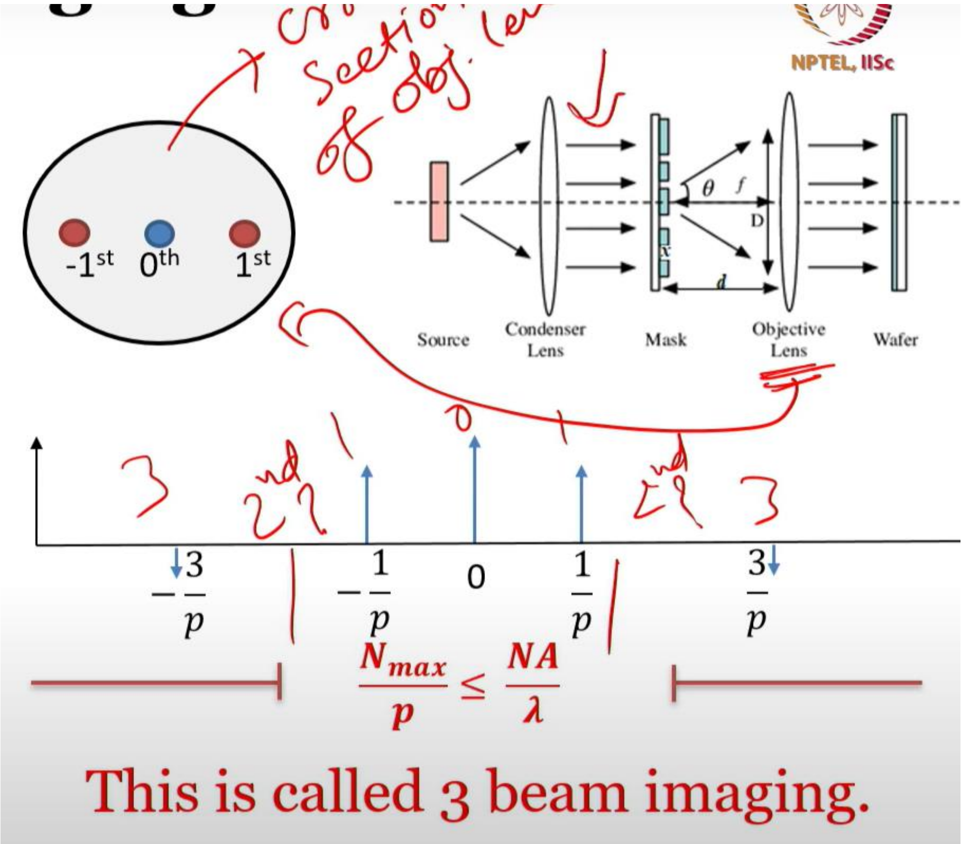
This is your electric field okay, and you square it up you will get a intensity. Now this is basis of how it is reaching again once you see this much intensity will reach here there are further analysis you have to find out you know dark spots and bright spots intensity shown or known as I_max and I_mean. Considering that there is something called contrast is defined that how your setting is treating your overall lights or both the lights differently when mask line width is there and not there okay. So that is again an important point.



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

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

So now we will see as I mentioned this is like a cross section of objective lens. You can see the objective lens here just a cross section of that it is showing that out of this many orders you have zeroth order, first order both sides, third order.



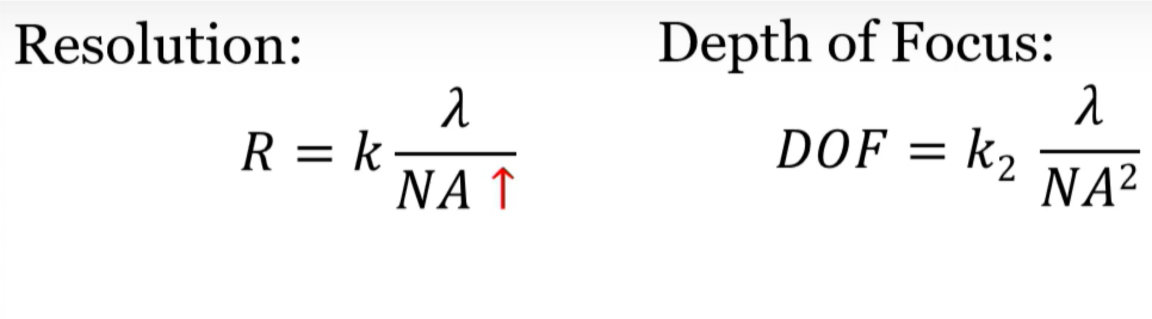
$$\frac{N_{max}}{p} \leq \frac{NA}{\lambda}$$

This is called 3 beam imaging.

Now a second order is not given because let us say in the destructive interference it has vanished. How it happened you can check in this particular link to identify why this particular order is not present. okay but the lens is saying okay I am that much big only that I can only cover till this point and this point. So, then you see that you are taking 3 beams into consideration hence it is called 3 beam imaging okay important point and here you see that light is incidented normally. So, in this case it is like that let us say if you change your light source this spectrum will get shifted by this side or this side as a result you will get only instead of 3 beams Again an important point of consideration okay.

So, we will see that in the near future.

So now we will see a 4 quickly we will see the 4 resolution enhancement techniques which an important process is to get your desired resolution okay. The first one of which is your immersion lithography. very important. So far now you see immersion means some fluid okay. So mathematically also if we think that immersion lithography value is more than like 1.3, 1. You know kind of how you can increase your numerical aperture in optics if you know numerical aperture is nothing but your n sin theta right where n is your refractive index. What if we can increase the refractive index? If you increase the refractive index, you will get a higher value of na. Now, you put a higher value of NA, you will get a lower value of resolution. So, that is your resolution enhancement and how do we do that by changing the medium. So, very simple you see this is your lens and this is your wafer on which resist is stacked.



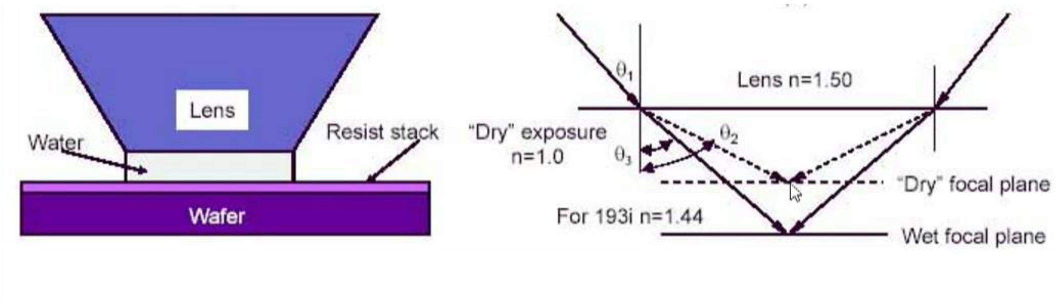
Resolution:

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

Depth of Focus:

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

This lens when I say I am talking about objective lens, in between so far whenever we have not mentioned it is air. But what if we change the medium from air to some fluid. As a result of that you see this N, Lenz refractive index is 1.5 whereas here you see it is 1.44. Here there are two examples also provided that instead of dry focal plane which is coming much earlier you can extend it to a further dimension which will help ultimately. in deciding where your wafer should be and what should be the distance and there is much more consideration. So, that is your you know when you are dry exposure and wet exposure you will get a different image, and it is known that with wet exposure you are getting better image. So, that is very good right we can improve the resolution but again there is 4 cases given at 2 different wavelengths and it is known that you know for the same numerical aperture immersion has a better depth of focus giving us more provision to placement of the objective lens.



Each and every good thing comes with its own challenges, okay. So, then what were the challenges when we are using immersion lithography okay again yeah this one side point is this depth of focus when you are using immersion lithography the same formula of depth of focus will not hold there is some slight change in that which is good because as I mentioned for immersion we are getting better depth of focus this we have already seen I have explained it while you know doing this particular thing so that is cleared and what are the challenges with that so first and foremost we are using fluid instead of air while we are scanning or exposing so the important point in this case is you see this are like you have to put the medium into that and even a smallest of bubble.

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

Last time I mentioned that if there is a slightest change in design or mask or process, it will get hampered, all the devices will get hampered, and you will not get a desired pattern. I was referring to this as well if you have bubbled a small bubble can result in a defect in mask and you might have to recall the entire device. So, it is very cautiously should be taken care also you see here there is a water and here there is a PR.

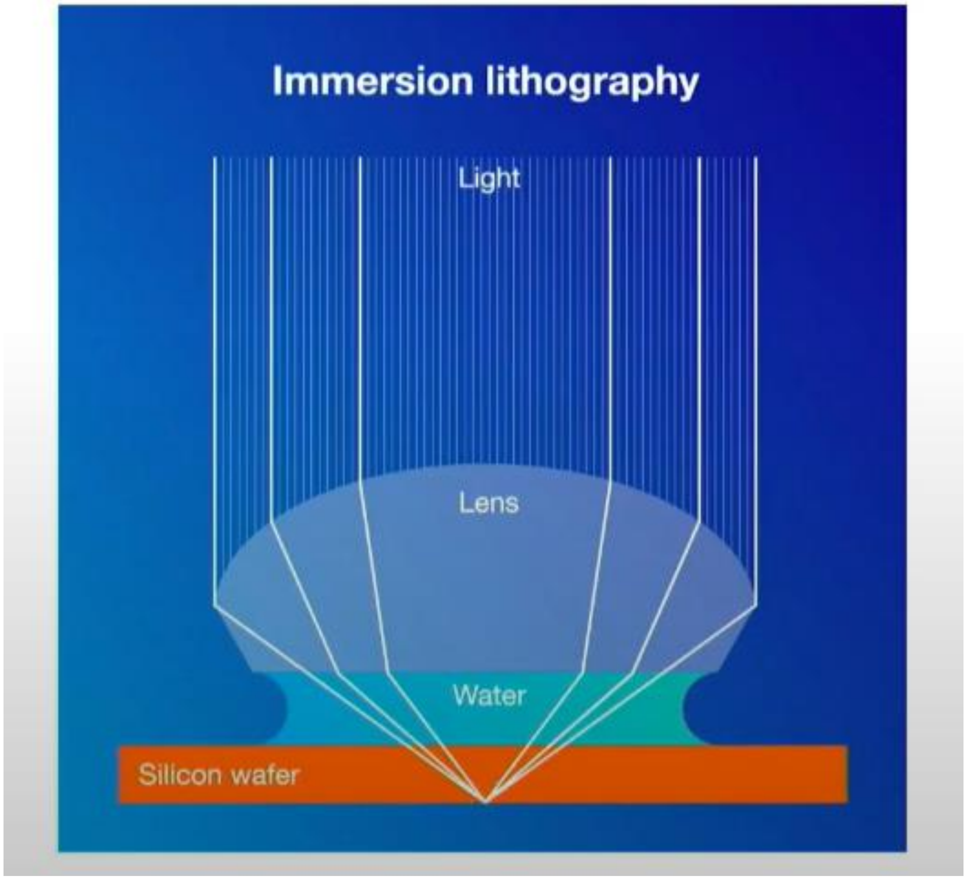
Now PR is a chemical with finite viscosity and properties. So that should not be changed. PR's own property should not be changed. So, there is something called guard or to guard the PR. There is one top mechanism that is being used.

I will come to that. So, then water interaction with PR you need to take care. Hydrodynamics delay. This, when you pour water at a certain flow with precisely you are pouring without any bubble and defect also, when you expose it, this exposure light is of a great energy, it can heat the water and then light travelling through might not reach to the exit next time or when you perform multiple runs, it might not be possible, hence you have to cool down. your water in, hold there and wait for some time or remove the water and put in new water. So, this all are like important drawbacks or challenges when you use immersion lithography. However, people are using it just to give you an overall small illustration I have added to these shots.

So, just please see this and you will get an idea how nicely or better you will be able to see things with lithography. This is a dry lithography. Now when you use immersion, you see the change.

I will play it again just to give you people an idea. This is a dry lithography. You are not getting proper focus you see here. Whereas, when you use immersion lithography, you are getting all beams converging to one particular point. Again, it depends on your scenario, but just a good illustration, so I thought of including it. Another very important point, resolution is not only about making things smaller.

It is about getting things more accurately as well. So, if somebody says that okay you are getting earlier 20 nanometer now answer 20 nanometer what new things you are adding upon that can be multiple things okay. So that is like a very good take away that if you are getting a better image also that is good thing okay. Ability to pattern smaller features on the top layer of the substrate, ability to pattern small size feature. Now this again we have already seen this I will not come to this, but the thing is immersion provides accurate features with better focus.



See this is the important trivia that 1984 it has been started okay. Well IBM confirmed that lithography can be done in or we are doing it in 2004, see 20 years, they have checked and seen through that whether it is good enough to go ahead or not. I was mentioning that cost factor is very important and whatever you are getting okay they have to cross check everything before proceeding with photolithography otherwise financially also a big loss and not every semiconductor giant can afford it okay. Also, I mentioned about topcoat, top layer should be properly isolated from water, so there should not be any form of diffusion between your PR and the liquid medium. And just to give you an idea that cost to do one particular run, one experimentation exploration, it is 30 million USD, only 248 crore rupees to do this particular immersion lithography. These are I think slightly one- or two-years older numbers but you can have 250 crore rupees then you can explore this particular thing and that is why they will take utmost care that the process will not fail, and you will get a desired product.

Immersion lithography is most widely used with highly purified water. I already mentioned anything which is less than 45 nanometer uses or sub 20 nanometer uses this kind of lithography. Now, we have been trying since 70s, 80s and all. Another fun fact is that oil immersion has been used for almost a century. Sometimes the things which is happening in front of you seem very easy, you might not find it obvious. So, that is like a fact that immersion was already used for microscopes and all, but we are reluctant to use it for this.

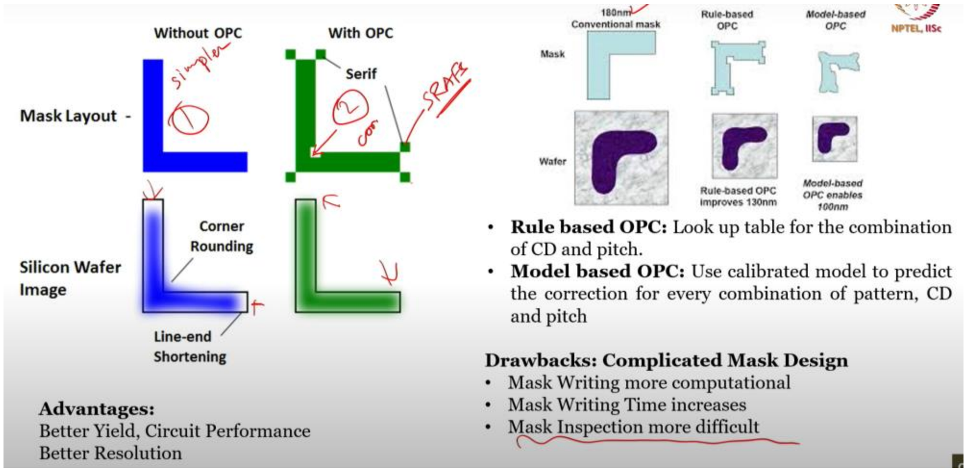
Now, it is being used, we are getting good results. So, that is one of the RET. The second one is optical proximity correction. So, this is another important point which I like to explain you see focus on this particular image you see there are two instances one is without optical proximity correction, and one is with optical proximity correction. These all are reasons why we are not getting proper image which is there in mask same thing cannot be obtained here there are reasons for that which I already explained there might be a non-linear response contrast might be difference you are not getting proper interference and all this thing. not go into too much detail but you see these are the two examples one is this other one is this okay. So, you see here that one one is without optical proximity correction this was your input mask this is what you could get on your wafer whereas this is with your proximity connection this was your input mask, and you got here.

All this abortion will slightly alter your design. So, if you already know that this kind of alteration happens, how can you backtrack it and get a better design on your wafer. So, this is an overall idea, it is like a closed loop non-linear feedback control system. You do this thing and evaluate the algorithm if it is satisfied great your mask design is done. So, this and all is like a prior step before loading mask and you have to add some additional features called ASRAPs, sub resolution assist features which are not actually a part of your design, but you have to use it and that will help in get the desired design. How do we do that I will show but prior to moving that fabrication process below 250 uses OPC optical proximity there is something called process proximity correction as well we will come to that.

But examples of this see why I have taken this example is you see this is without OPC this is with OPC okay and you are getting desired pattern below which is shown but the blue one you are having several things including line and shortening you see you are not getting a proper ending at both the sides compared to the green one what you can see here. Why do they get this particular thing is because of this kind of serifs or SRFs added, sub-resolution assistive features, very important thing and you have to add. How do we come to know that we have to add it here? You see this is not only about adding, from this thing it has been edged also. So, there is known data, and you know now with the advantage of machine learning and all known shapes using which you can identify which kind of pattern finally we get generated on the wafer.

So, here you see 180 nanometer technology which has been a very prominent technology node in terms of VLSI. And there are two things, one is rule based and one is model based. Rule based simply works on lookup table thing, whereas model-based work on the calibrated model. There are different shapes instantiated, so you can use that and get your final thing, okay. There are drawbacks as well, thus mask writing is more computational. You see this mask, mask number 1, mask number 2, which is more complex, of course number 2, but gives its own fruitful results.

So, mask writing is computational, if it is more computational time will also increase and the most important and the biggest challenge is your mask inspection is more difficult. Let us say you are not getting a desired pattern, you have to backtrack to your mask, then what went wrong or which shape has a problem, this is simpler to understand and analyze, this is complex. but with that we are getting good resolution or accurate resolution, okay. So, this is another point, another OPC.



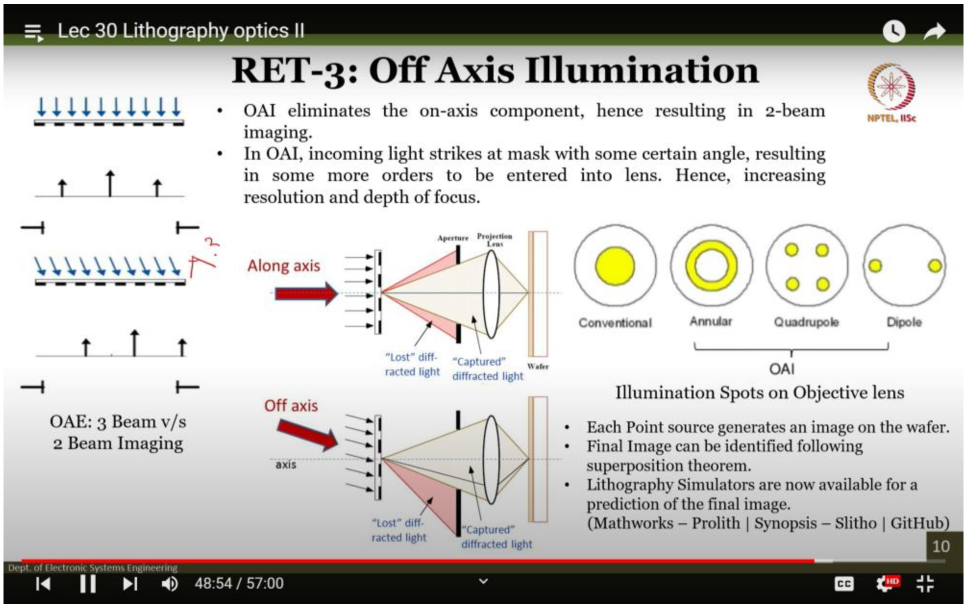
- **Rule based OPC:** Look up table for the combination of CD and pitch.
- **Model based OPC:** Use calibrated model to predict the correction for every combination of pattern, CD and pitch

Drawbacks: Complicated Mask Design

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

Advantages:
Better Yield, Circuit Performance
Better Resolution

We will see the third OPC which I already covered, so I will not go into the detail of that, off axis illumination. Just quickly, this is 3 beam imaging versus 2 beam imaging. This is the case of 3 beam, right, because you see that beam number 1, beam number 2, beam number 3, okay, is passing through because of this normal incidence. Whereas if I talk about this case here you see beam number 1 and 2 is only passing where third is due to the you know finite range of that is not getting passed through. So, this is 2 beam imaging how when it is possible you see this is normal incidence this is oblique incidence.



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.

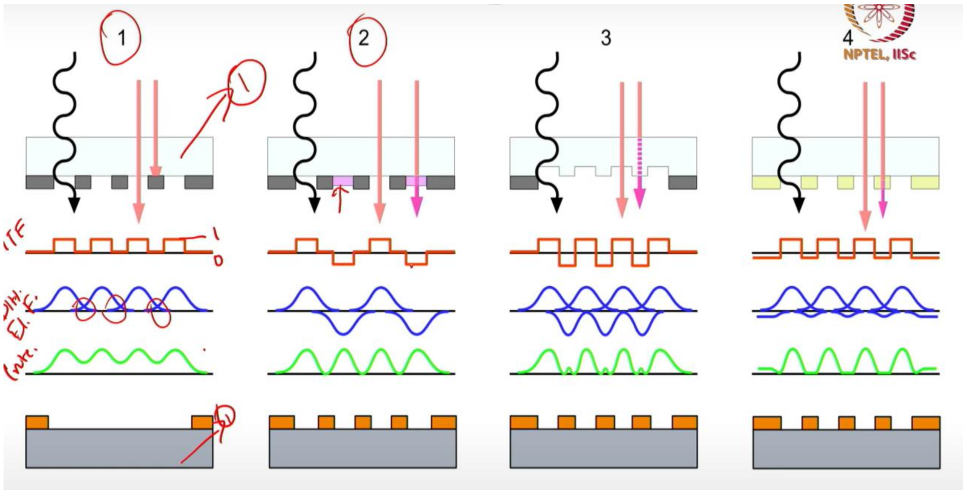
OAE: 3 Beam v/s 2 Beam Imaging

Illumination Spots on Objective lens

- Each Point source generates an image on the wafer.
- Final Image can be identified following superposition theorem.
- Lithography Simulators are now available for a prediction of the final image. (Mathworks – Prolith | Synopsis – Slitho | GitHub)

You see here along axis or normal incidence and off axis or oblique incidence. okay and also, there is a method to illuminate a particular source so that also we can consider that whether it is conventional like this or it can be annular and all you can explain you can kind of swim by yourself and check which particular formation gives you better image. And this I already explained that each point on the source generates an image on wafer. The final thing can be calculated with superposition theorem but nowadays before calculating there are simulators available from Mathworks and Synopsys and also available in GitHub as well. I would strongly encourage you to check all these softwares and know how the final point or final image on the wafer is being calculated. Finally, the phase shifting mask, so this is your phase shifting mask, there are 4 cases, I mentioned that sometimes you see this thing.

It is blocking the light right. So, generally the chrome glasses which have been used for masks only modulate the amplitude of the light and not the phase. But if we use some particular material that will help in changing the phase of the mask and as a result of that by adjusting the thickness of quartz you will get any phase difference. When you get any phase difference you can check what an all you know image you are getting on your wafer okay. Overall, 4 cases will be given we will see all cases one by one so you see case number 1. Case number 1 is nothing but binary mask okay this is your mass transmittance function red one is your mass transmittance function this one is your diffracted or light diffracted electric, and this is intensity okay.



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 Intensity on Wafer, (Bottom) Resist on Silicon Wafer

So, you see here this is simple mask what we have been seeing this is 1 this is 0, 01010 simple you are getting this kind of deflected pattern whereas I mentioned side lobes gets eaten by each other and you will get this kind of intensity okay. And with this intensity when you reach a wafer your PR will get affected like this and you will get this profile see what your profile was or what do you want in mask compared to what you get here. Let us see the second example now. Second example, you are using an inverted mask or phase shifting mask by 180 degrees.

So, you see when light is passing through 1, when it is not passing through 0, when quartz is there, it is inverting. So, you are getting 1, 0, minus 1, again 0, 1, 0, minus 1 like that. As a result, you are getting this kind of pattern. And when this pattern is there, when you square it up to calculate the intensity, you will get this intensity pattern. When it reaches to your wafer, instead of what you are getting here, nothing was here.

You are not getting any features which you want. Now, you are able to get the features here. So, that is where your resolution enhancement happens. This is another case. If you take the third case, it is halftone mask or etch Quasmark or Levinson mask that is your third mask. So, you are getting see here it is etched itself that mask only itself is etched.

In this case, you are getting let us say 1 half, 0 and minus 1 half like that. So, there you are getting this kind of electric field resulting in this intensity and you are getting this kind of feature which is closer to what you want. And finally, if you are using a half tone mask, it is one half and 0 or something like that. So, based on the thickness of this thing, you can tune the mask transmittance function that is where everything begins. And then you can calculate your intensity to get an idea that how solubility of PR will change.

This of course, after development, after exposure you have to follow all the post exposure bake and development and all the steps. So, there are some more further techniques which is kind of considering time constraint I will not go into the detail but I strongly encourage you to check that there is double patterning and triple patterning nothing but you are doing the same patterning things twice by shifting a mask or using two complementary mask and three complementary mask. In a nutshell if you have a 60-nanometer design if you use double patterning, you know you are getting earlier 60 nanometer pitch if you use double patterning. you will be getting around 30 nanometer or if you use triple patterning, you will be getting even your resolution gets halved that is why it is known as LELE litho etch litho etch or litho etch litho etch litho etch. Now we can further go and get as small as possible right sounds very good but when you are using multiple times lithography and etching it comes with its own cost and complexity. Hence people limit to repeating this thing in one exposure only if you are getting that is affordable and better and that is where all the magic what I have quickly discussed in this phase shifting mask or off axis illumination or optical proximity correction or remotion lithography comes into the picture.

Just to give you an overall idea you see this thing this is your growth in terms of VLSI. Last time I mentioned that okay resolution gives you 50 nanometers, how can we reach from 15 nanometer to 2, 3 nanometers. So, the agenda of my today's session was to make you people realize that oh yeah if we do that we can reach to this particular point. When you go from here to here, when you go from 20 to 5 nanometer or getting device dimension as small as possible, you have to add more and more magics here. Here it is not mentioned but all this thing uses immersion, all this thing uses proximity correction, optical projection, all this use oblique illumination. Along with that there are some selves assist double patterning or that is a double patterning you see 2 different colors in mask whereas in triple patterning 3 different color, quad patterning 4 different color.

Based on your budget, based on your process flow, based on your system you can explain, or you know implement any of this. So, these are like you know 4 techniques which I wanted to discuss quickly and make you people realize how can we reach. from 50 first lecture I try to explain how we can reach till 50, 60 nanometer in this class I try to explain how we can reach from 50 nanometer to 2 to 5 nanometer. okay but still as I mentioned people are still going ahead and making device with 2 nanometer 1.5 nanometer how it is possible. So, if time permits, we will see that otherwise there is something called EUV and all I would like to discuss you know I would like to encourage you to check extreme UV lithography and all this thing E-beam lithography, and all combinations of several resolution enhancement techniques comes together to get your final device.

okay so that is it I have for this lecture if you have any questions, or something feel free to connect with me email me we will be very happy to answer that questions go through this thing very important both the lectures and try to understand how we can get the desired pattern from your mask to wafer with desired resolution okay fine. That is, it I have for now.

Please take care. Bye.