Biomedical Ultrasound: Fundamentals of Imaging and Micromachined Transducers

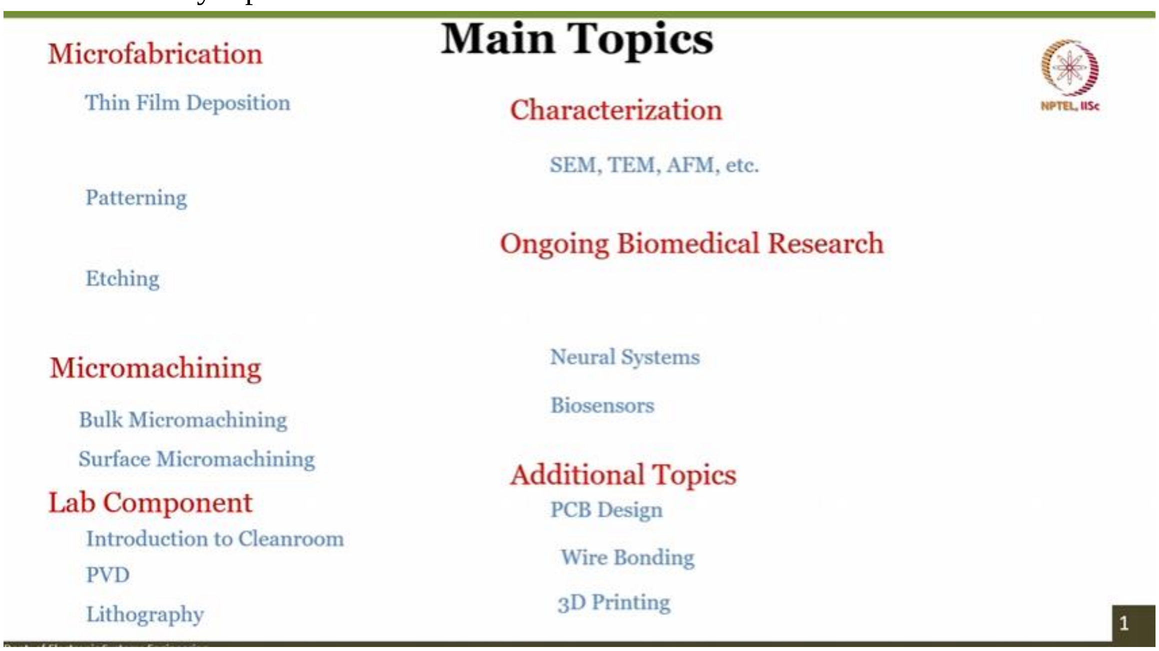
Prof. Karla P. Mercado-Shekhar, Prof. Himanshu Shekhar, Prof. Hardik Jeetendra Pandya

IIT Gandhinagar, IISc Bangalore

Lecture: 29
Lithography optics I

Hello everyone welcome to the course this will be a 2 part TA session on a specific topic in lithography. So far in the course, professor would have taught about several micro machined sensors or micro sensors for various different applications. Before we start the topic of lithography, I will just quickly glance through some of the which are covered in the course, and some that will be covered in a near future.

Some of the key topics which has been covered so far are listed below.



Micro fabrication can be for different applications like micro heater, interdigited electrode (IDE), micro cantilevers, micro sensors etc. So, microfabrication and micromachining have been taught in a greater detail by taking examples of process flows.

Additionally, one important part of the course is a lab component in which we try to realize or try to show how all this concept work in a real world. So, in that you will be seeing what clean room is, what are the protocols needs to be followed while entering the clean room, gowning, de-gowning etc. So, these would be covered under the lab component. Moreover there will be live demonstrations of some of the systems which will help in realizing the process called microfabrication.

Once you fabricate anything, it is very important to identify whether it is correctly fabricated or not. That is where characterization comes into the picture. As the name suggests, the devices falls under the micro to nano range, which is around 10^{-6} to 10^{-9} meter and of course it is even smaller than our one hair strand. It is not possible to do this by mere visual inspection you cannot see that device. Also, if there is a device with a dimension of 50 nanometer and 20 nanometer, you would not be able to check whether it is of the same dimension or not. So there are several characterization techniques for this.

Characterization techniques can be contact or contactless. Most of the contactless techniques are optical techniques like scanning electron microscopy, TEM etc. Equally important as fabrication is the term, *V and V*, which stands for verification and validation. In this course, we will try to cover some of the ongoing translational biomedical research as well. First we have talked about concepts like micro fabrication machining. How do we realize that? There comes lab components with which we realise these sensors. Once you understand the concept, realize it into the real world and then you are checking where you can use it. So those are the translational applications which you can use it. So some of the ongoing research or recent trends in this biomedical research will be briefly discussed. Finally there are some additional skills which is required to make a particular system out of it. So, these are some of the main and subtopics which will be covered. So, as it is mentioned thin film deposition, patterning, etching will be the part of microfabrication.

Now, microfabrication is an overall process consisting of several sub processes, the first one is you deposit a particular layer known as thin film deposition. It can be done in a physical way or the chemical way. So if it is done in a physical way, it is known as physical vapor deposition and if it is done in a chemical manner, it is called chemical vapor deposition. This is an additive process, which means you are adding something on the top of substrate. Now what should be the thickness of that layer and its material? All these depends on your final application and is decided by the process flow.

Once you do that, you want a particular design on the top of that. So, that is where patterning lithography or photolithography comes into the picture. You will be using masks to do this. So mask is where your entire design starts. Using that mask you will be able to get the same design, or you are targeting to get the same design on your wafer. Will we get that? That we will see in this class. Whether we are able to get the same thing on all devices. How it happens and how optics play the role. All this things we will see into this particular lecture. So patterning is a process where you will get your desired design from your mask to your substrate.

There is one more process called etching, where you want to selectively etch out a particular portion on your wafer. There are different types etching. Contrary to thin film deposition, which is an additive process, etching is a subtractive process which will remove one particular desired part from your wafer. It can be done through several means such as deep reactive ion etching, RIE etc. So that will be covered under this course and also bulk and surface micro machining is also discussed. I have already mentioned the key processes of fabrication like PVD and CVD. In PVD, there are multiple processes like thermal evaporation, sputtering and e-beam evaporation.

Further, for characterization, optical imaging techniques will be there. SEM, CEM, AFM etc. Another important point is, we will be covering tissue engineering, neural systems development and biosensors under the recent trends in this course. Additionally we will cover how PMUTS are being developed from fabrication point of view as well as how it can be useful in clinical world for translational application point of view. Finally, we will see three of another important skills which are useful for making any electronic system one of which is PCB design.

So when you have your microchips, these chips should talk with each other. The output of one microchip should be given to another. How do you do that? In the design phase when you are making any micro fabricated device you will put a contact pad to communicate with external world. How the process flows from sand to silicon wafer is one science. Once wafer is ready how can you make microchip from that wafer is another science. Once chip is designed, how can you use that chip and make a system out of it is another science. And of course, how you use it. So, this is of a system development point of view. PCB Design is important for this topic.

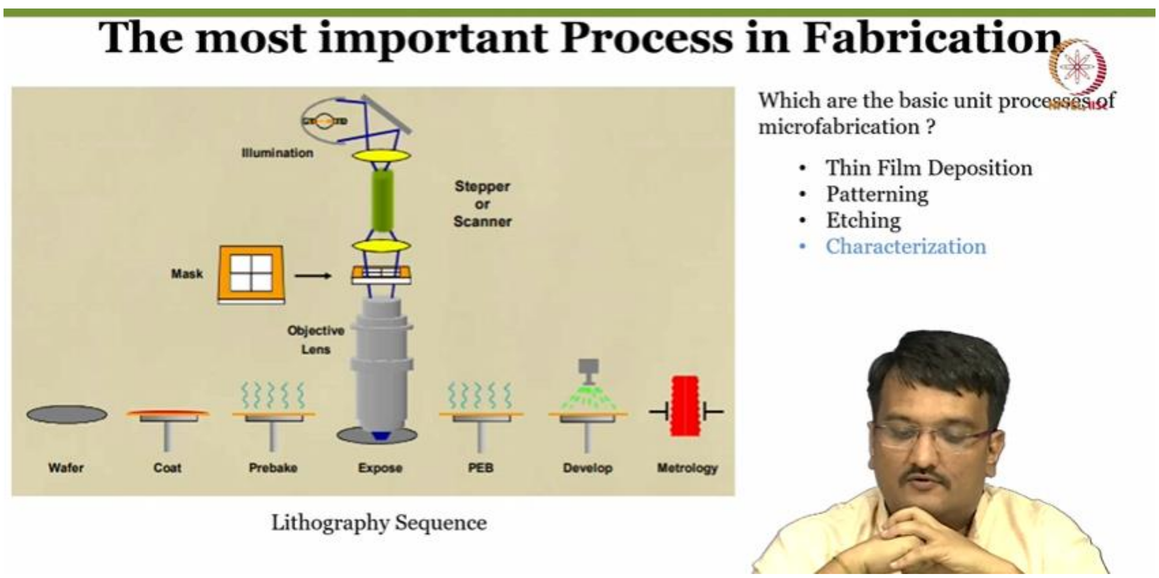
Once you have a sensor, which will be a very tiny 1 centimeter, or 2 centimeter, then how will you make sure that particular sensor will talk with your external world? That is where PCB design comes into the picture. Instead of using multiple wires going from one module to another module, you can create robust interfaces by making a small PCB. It will be covered in this course how analog electronic modules are designed and customized for your application.

Further, once you have that contact pads, it should be wire bonded. So, all your sensors should be properly intact when you want to take any electrical signal from your chip to the outside world. For that it should be wire bonded. Also, wafer dicing is also another point because if you have 4 inch wafer, it will have a small unit of sensor will get be replicated 100 times. Then you have to take it out right or extract all 100 instances. That is where dicing comes into the picture. How you can cut it to get a desired pattern and you should know where in your wafer the desired patterns are.

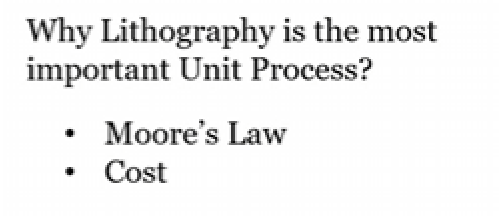
So after characterization, you can identify the coordinates and dice the wafer to get your multiple microchips. This is the beauty of VLSI that you will get a small chips and they are getting smaller and smaller. In one wafer itself, you will get thousands of units and hence we are seeing the decrement in terms of price.

So again a very important point is 3D printing. When you want to make a casing for the sensor, or you want to make a device user friendly, you want to protect a particular unit or circuit from disturbances, 3D printing comes into the picture. Again 3D printing itself is a huge area, there are multiple methods available like stereolithography, FDM etc.

So, now we will go to one step further and we will see what is the most important process in fabrication. So I would like you to pause and think, what is the most important process. There are 4 options: thin film deposition, patterning, etching and characterization. So, here, I have written characterization in blue. What is the reason behind that? These are different processes, thin film deposition, patterning and etching. But characterization is important because characterization validates your design or developed design. However, from this entire fabrication point of view once you get your desired design that is optimized, then your process flow is validated, verified and confirmed and you do not have to do characterization. That is where the other three processes are important and out of which one of the most important process in fabrication is patterning.

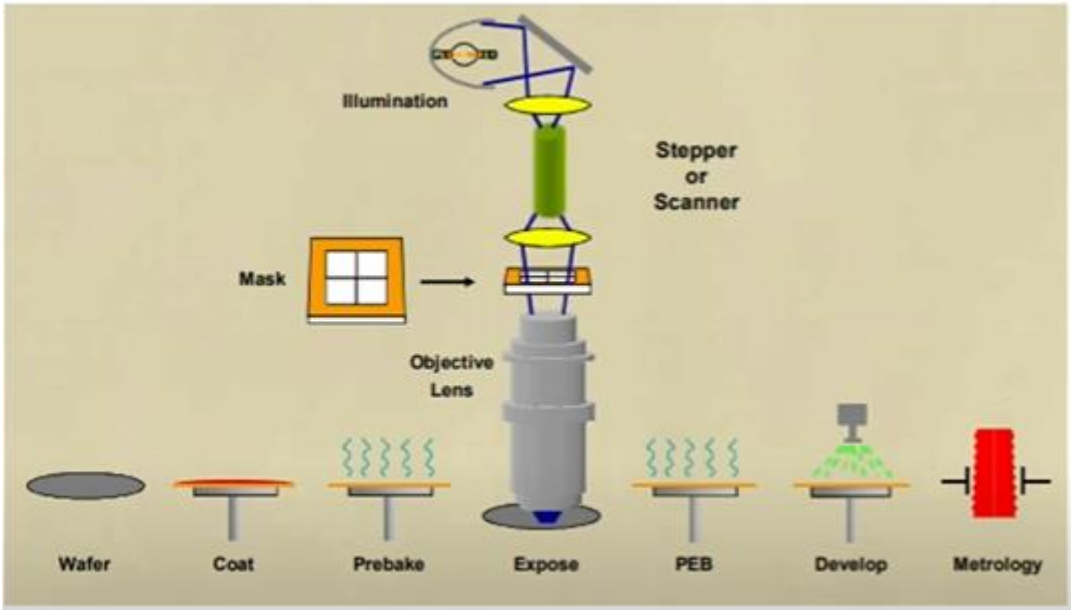


Why patterning? There are multiple reasons, and one of which is Moore's law. Gordon Moore was the founder of Intel and subsequently Fairchild semiconductor, if I am not wrong. Based on his experience working with semiconductor devices has come up with his own observation, which is known as Moore's law, I believe it has been followed for last 3 to 4 decades. What he said is that at every 2 years, the number of units or number of devices that you can put it in the same area gets doubled. When the first computer was made, it was almost the size of a room. But ultimately, now your entire world is in your palm using mobiles. The growth in microelectronics and shift in VLSI industries have caused this. So Moore's law as an observation empirical observation has been followed for last 3 decades Another technical reason for lithography’s importance is that there is a force behind why we are able to follow this Moore's law and you see the rapid growth in electronics industry. Cost for any company or business is very important. How much you are investing and how much you are getting is in fact the main purpose.So there are two reasons behind the importance of lithography, one is Moore's law other one is cost. It has been noticed that almost half of the cost of any microfabrication process is being spent for lithography.



One another important point is that all these micro and nano structures are even smaller than our hair size. Minute of differences can result in defects. Let us say you have a very small defect in your mask, a possible shot. This shot in your device can completely defeat the purpose of your development. Now in your mask, if there is an issue, it will get reflected 100 times in your wafer. So all your device will be faulty and as a result of that all your devices will be faulty. Ultimately you have to recall the device. This has happened with microfabrication industries before. You might have to recall all the devices and there are proofs in the past that companies has been completely destroyed because of one recall in the semiconductor industries. Hence, from companies growth point of view and also from the finance point of view, lithography is a very critical process.

How is lithography being done, so the figure you can see is a process flow of lithography.

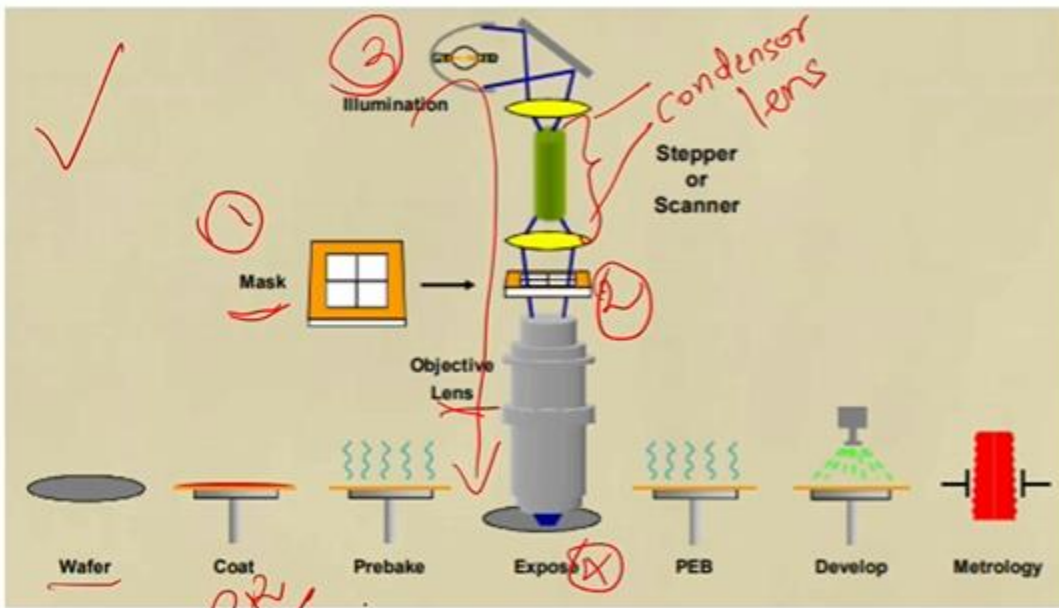


Lithography Sequence

When you do lithography you have to make sure that your deposition is done. Once you do that you take the wafer an if required you clean it and make it ready for the process. Once you do that you will coat photoresist, which is a very important step. Photoresist has two types, positive and negative types. These two types, react to the light differently. In the figure, you can see that the process will start from mask. You will design your mask and load it. Then you have to identify and illuminate a particular source, as seen in the figure. There will be multiple lenses and they will be called condenser lens. When I say condenser lens or objective lens, it is not one lens instead, there is a group of lens strategically placed at a certain distance so you will get a desired image. Ultimately the entire lithography game is on how light travels from illumination source to your wafer and how you can control and precisely manage the beams of light. This is why photolithography is a very important point.

The main principle behind it is diffraction. We already know about reflection, refraction, diffraction, constructive interference, destructive interference, which are the main basis of why we are getting a desired pattern on the wafer, and why we are getting our proper robust microengineering device, microelectronic device, microchips and all the systems, Coming back to the point I was talking about that the process starts from mask, then it will be loaded, and then finally it will get illuminated. Once you illuminated it, the exposure will reach at the point labelled as “expose” and optical parts will end where your PR is coated. Now, PR is photoresist which is getting coated by something called spin coating. If time permits, then we will show the demonstration spin coater which coats your photoresist which is a semi liquid chemical with a finite viscosity.

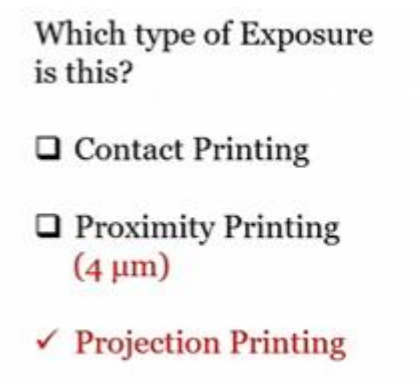
When you pour PR on the wafer and you spin coat it, based on your spin speed, it will decide how thick your PR will be coated and that is already been calculated prior because your light which is coming from your illumination to your exposure will have a certain energy, so that it can change the solubility or chemical property when it is exposed. There will be two types of region on the way for where light is exposed and not exposed. So ultimately it will be mapped into two regions. Where light is exposed, some solubility X and the other one is where light is not exposed the solubility Y. The difference between that will exposed to developer, and then you get a final pattern. Also there is pre-bake and post-bake. Pre bake is like a soft bake. Post exposure bake is a hard bake. For each and every PR, the temperatures and timings of this particular pre bake and post bake are known.



Lithography Sequence

So far we have understood that we will make all these micro sensors using fabrication and in that, lithography is the most important process. Let us now go deeper and understand what is most important in lithography. In lithography process flow, the first is wafer preparation, then coating, pre-bake, I will consider the entire fourth step as expose, post-exposure bake, development and metrology. This metrology is nothing but characterization. So these are the seven steps in lithography. Which of this steps is the most important step? I would say that exposure is the most important step. I have mentioned that optics imaging and exposure are the most important. There are two points behind the first is Moore's law which I have already explained and the second one is more important as it defines your CD. CD is the critical dimension which is the smallest possible dimension on your device. Some of you might have heard the term pitch or semiconductor pitch. It is around 45 nanometer, 10 nanometer, 5 nanometer etc. These are your critical dimensions. So the most important step in lithography includes everything which are highlighted in blue color.

So, does this mean other process or sub process are not important? No they are also very important. If any one of this process fails or not optimized, you will not get the desired result. But when I talk about coating, or about pre-bake, or other sub-processes, they have been optimized or saturated when it comes to improvement. However, there is still some magic left in exposure or optics, which can help to take this bandwagon of miniaturization in microelectronics further. Now let us see what kind of lithography or printing is happening here? The type of printing in the figure above is Projection printing. It is based on the projections of light through lens, through mask and then coming to your device. The other two types of printing are contact printing and proximity printing. So in contact printing, you have your things on your mask and you put that mask on the device



Now, this has some limits. Let us say if I talk about contact printing the mask an device is placed in contact, and the number of times this kind of exposure or contact can be done is limited. Hence you cannot get multiple devices with one mask. So you have to keep on generating mask also keep on generating device also.

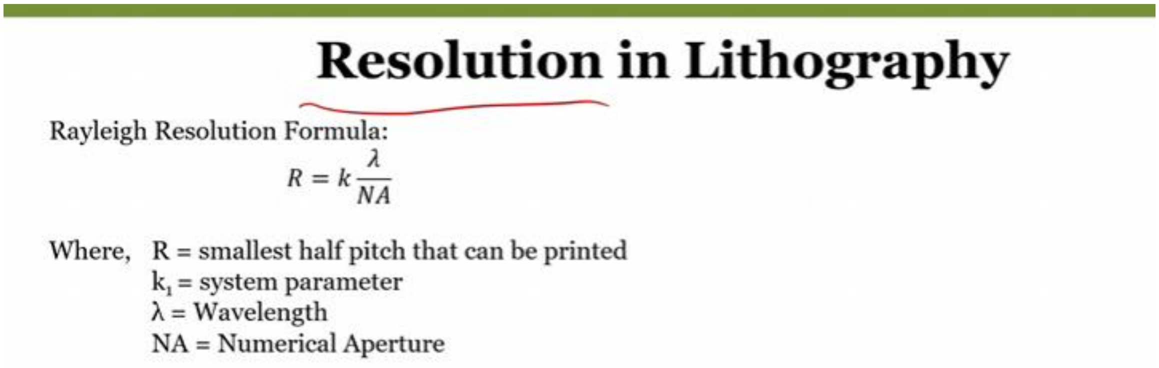
Then we move on to proximity printing where there is a finite distance between your mask and devive. However, proximity printing will work till 4 micrometer.

The current technology is using few nanometer sized devices. So the current devices demand for a really low pitch in the nanometer scale and the field has shifted to proximity printing.

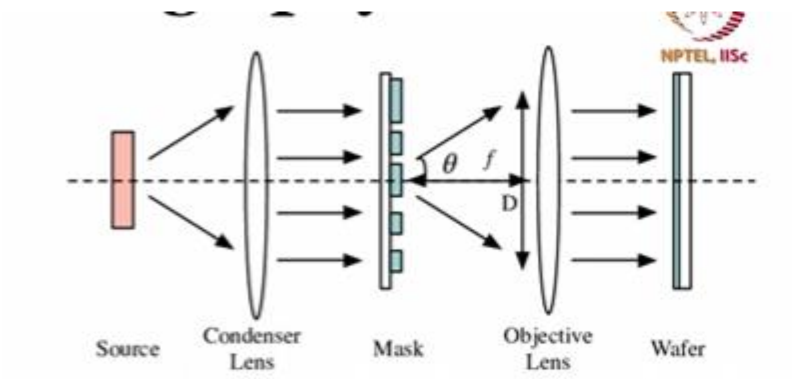
Now, let us talk in detail about lithography. The most important factor in lithography is called as resolution. All the leading microelectronics companies, say Apple, Intel and all these companies' final evaluation parameter is resolution. How much smaller dimensions can you successfully reproduce on your wafer. This is the final metric. If you study anything in this course, then your final evaluation could be the skills what you have learned and also a little bit of marks you get. Similarly in lithography or electronic companies, the resolution is the important parameter. Rayleigh has come up with an empirical formula which is true only for projection or diffraction based lithography. His empirical formula is,

$$Resolution = k\lambda/NA$$

Where, k is your system parameter that depends on how you are illuminating the source and other system parameters like the angle of illumination. λ is your wavelength and NA is the numerical aperture. Numerical aperture is the property of a lens to acquire light.

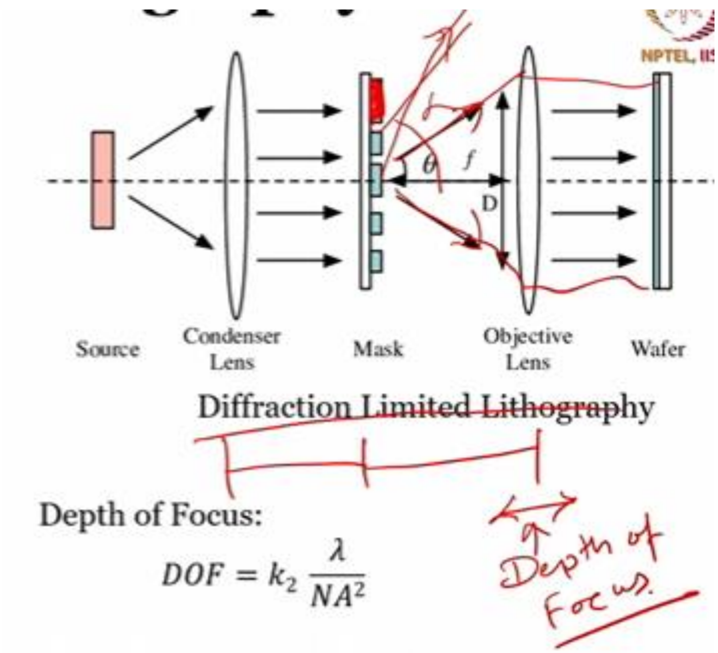


The figure below is the simplest yet most informative kind of illustration of the diffraction limited lithography. So you see that there is a source, condenser lens, mask, objective lens and wafer.

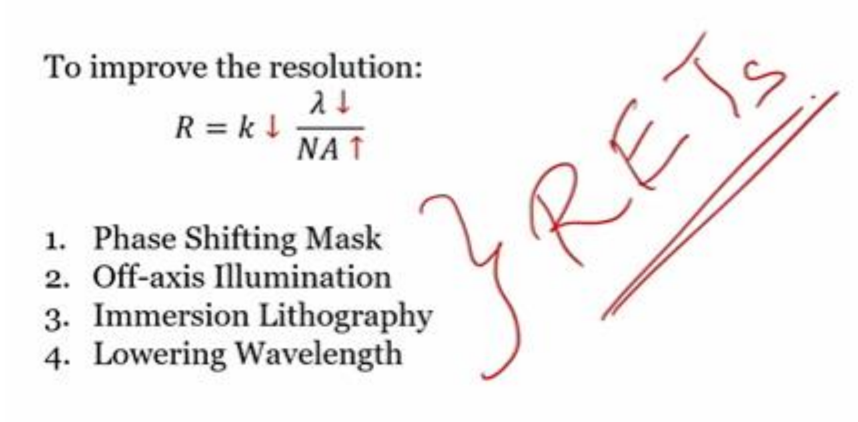


Diffraction Limited Lithography

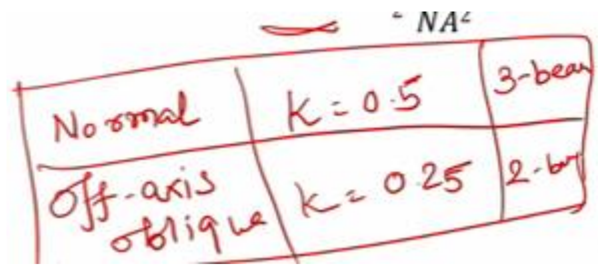
The same components that you saw un the previous system diagram is rotated and shown here. For the sake of simplicity only one condenser lens and only one objective lens is shown The source illuminates the mask, which is shown in blue color. Mask will not allow the light to pass through it and only a certain portion of the light passes beyond the mask. So your design of the mass will get reflected on the wafer. After that the light gets diffracted from the mask and let us say it is getting diffracted at an angle theta. The diffracted light reaches the objective lens and finally fall onto the wafer. What if the diffracted angle is more? In this case, the objective lens may not receive the light beyond a certain angle. So, this is where your numerical aperture of lens comes into the picture. Ability of your lens to acquire certain amount of light is the numerical aperture. Higher it is, you will get a better picture. You can also see from the formula that if numerical aperture is higher, your resolution is less. Smaller value for the resolution signifies a better resolution. Also, the depth of focus is another important optical parameter All these depends on your interference and on your path delay or path difference between two particular beams that get divided and how much separated are the mask, condenser lens, and the objective lens



If numerical aperture is higher, it is good but then when numerical aperture is higher it will lower down your resolution but it will keep the DOF (depth of focus) even less. So, the problem is you have to very precisely locate the objective lens which is again a difficult thing. So eventually to reduce your R, you can reduce k, reduce the wavelength or increase NA.



The four techniques above are known as RETs, which stands for resolution enhancement techniques. Each of them will be separately covered in the next class. One is phase shifting mask, generally mask only alters your amplitude or gets it diffracted. If you can change the phase also. Then some differences in terms of interference will occur and as a result you will get a desired pattern. Another point is off axis illumination. Currently if all the waveforms are normal to the mask. So this is a normal incidence. But what if I do some magic here and instead of normal incidence, my wave falls on the mask at some angle. This will affect my k parameter. If there is a normal incidence, then k= 0.5. and if it is off axis then your k value is 0.25. If I go one step ahead in terms of optical interference, my normal imaging or normal incidence will be 3 beam imagingbut I can also have 2 beam, which will be discussed further.



There is also immersion lithography. The medium between objective lens and wafer, when it is not specified it is air. But if you change it by water, it will affect NA. You know that NA depends on your refractive index and water's refractive index is bigger than air. So when you change it to water you will get some higher NA and as a result get a better resolution. And finally lowering wavelength. That is also important point because when you lower the wavelength, you have to take care of so many other things because when you lower the wavelength for any EM wave it will increase the energy, and this should not be high such that that it will affect or gets reacted by anything in between the medium.

Now we will quickly see some examples, which might be helpful for some assignments or exam at some point of time. The most important point is that you should know what is the physical inference out of it.

First numerical says that a PR gives a final resist thickness of 320 nanometer when spun at 2800 rpm. what should be the spin speed if you want 280 nanometer of coating.

Numerical#1: A photoresist gives a final resist thickness of 320 nm when spun at 2800 rpm. What spin speed should be used if a 280-nm-thick coating of this same resist is desired?

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The first thing you should know is the relationship between resist thickness and spin speed. Now it is very evident that if you spin at a higher speed, you will get a thinner coat. If you spin it at a very low speed then you will get a really thick layer of PR. But how much thick or thin will you get based on your spin speed? If you see this formula, out of four parameters, three things have been given and you can find the answer easily.

Solution: Resist thickness is inversely proportional to the square root of spin speed.

Hence, $\frac{d_1}{d_2} = \sqrt{\frac{\omega_2}{\omega_1}}$

Therefore, here $\frac{320}{280} = \sqrt{\frac{\omega_2}{2800}}$

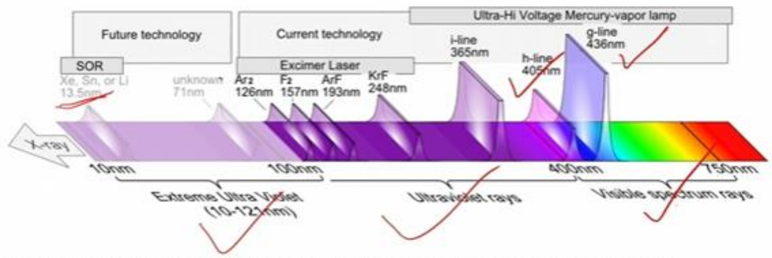
Solving it, $\omega 2$ = 3657.1428 rpm

But you should understand what is the physical significance. We are talking about PR coating which is a sub process of lithography, which is in turn a sub process of micro fabrication. Also you can see that the earlier thickness was 320 nanometer and now you want it 280 nanometer. So you have reduced it by at least some 10 to 15 percentage but you need to increase your spin speed by almost you know 20 to 25 percentage. So how it is correlated and spinning it at a higher and higher speed has its own consequences. Sometimes when you spin very high you will not get the desired output because of non-conformal thickness of PR. It might be localized or more formed in the edge beads. Edge bead removal is another important part of lithography. I would like to strongly encourage you to check what is edge bead removal for PR coating.

Second example is, what is the ratio of minimum feature size achieved using G line and H line wavelengths of a mercury arc lamp.

Numerical#2: What is the ratio of minimum feature sizes achieved using the g-line and h-line wavelength of a mercury arc lamp? Consider that the same photolithography system is used.

NPTEL, IISc



Solution: Minimum Feature Size or resolution can be defined as the following formula.

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

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

For the same system, $\rightarrow \frac{R_g}{R_h} = \frac{\lambda_g}{\lambda_h}$

$$\frac{R_g}{R_h} = \frac{436}{405} = 1.0765$$

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Now here, mercury arc lamp is used as an illumination source for a long time consider that the same photolithography system is being used.

So here, the lenses is same and the way you are illuminating your lenses is also same, which is in other words saying that your numerical aperture and k remains the same. Now The figure is to give an idea of what is G line and I line. This is an energy spectra. When you are doing some experiment, the peak will be present in when it has the highest energy. This will help us to use it in lithography as a illumination source. So now in this particular problem statement, it is written G line and H line. You can find G line and H line from the spectra. The ratio of resolution is asked in the question.

Here, the same system is used and hence we can consider numerical aperture and K value to be constant. Finally when you put the values and take the ratio and you will get a value that is equal to 1.0765.

The third example is,

Numerical#3: In an optical lithography system, a KrF source is used with two-beam imaging. Consider the Numerical Aperture as 1.35. Compute the optimal resolution that can be obtained for the given setup. (b) Will the given parameters fulfill the requirement if a process requires a 60 nm pitch?

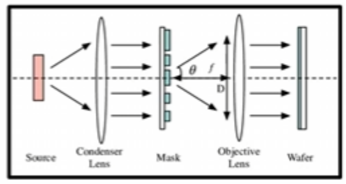
2-beam

K = 0.25

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



I already explained that 2 beam means K value is 0.25 Now you know the source, so wavelength is also known. So you got lambda, NA and from direct substitution, you will get the resolution, which comes out to be 45.92 nanometer.

Solution: For KrF, $\lambda = 248$ nm, NA = 1.35

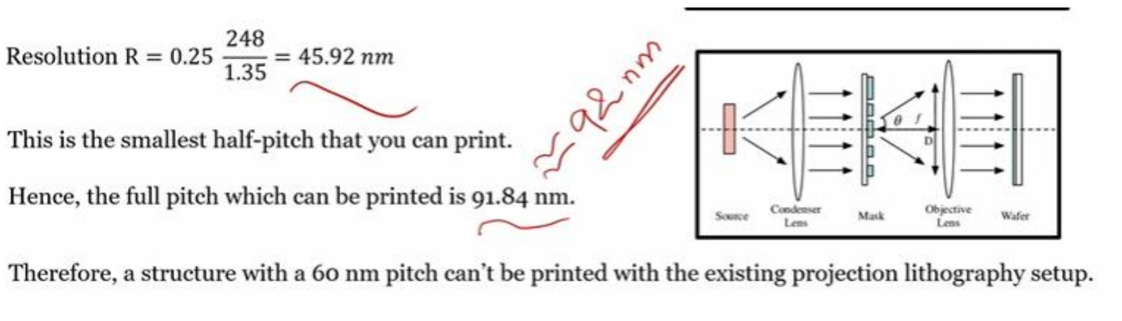
For 2-beam imaging, k = 0.25.

$$\text{Resolution } R = k\,\frac{\lambda}{NA}$$

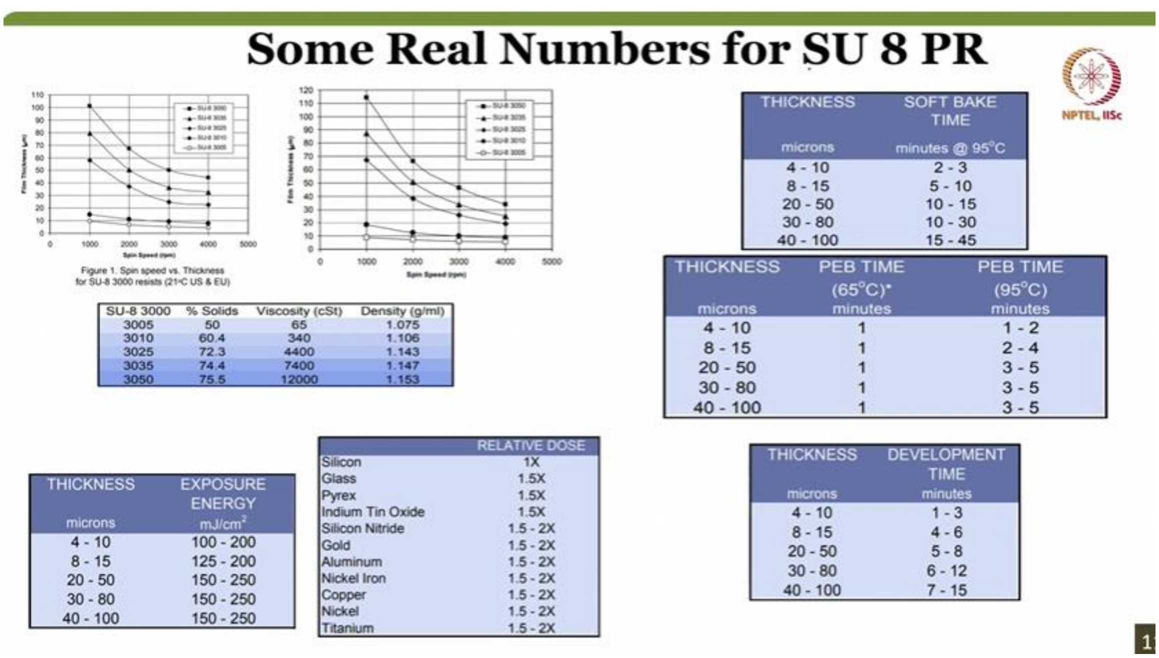
$$\text{Resolution } R = 0.25\,\frac{248}{1.35} = 45.92\ nm$$

Resolution is the smallest half pitch, which you can successfully produce. In the next part of the question, a 60 nanometer pitch is required. From the resolution value, your full pitch is around 91.84 which is almost 92. Remember that you will never get the ideal or calculated value when you do the fabrication process. It will always be a little bit more. So, consider 92 nanometer as your final outcome.

So, will the given parameters fulfill the requirement if a process requires 60 nanometer is the question. Now based on the lithography system details that have been provided, it can successfully produce 92 nanometer pitch. You want to go even lesser than that. Can you do that in this system? No. Then how do we do that? So, with this system or given scenario, we cannot print 60 nanometers but there are some more resolution enhancement technique that you have to perform. So, that is what we will see to improve the resolution.



Now, this is a quick point which I want to put because all of you know what is photolithography. It is very important to know what are the actual values. So, this is for SU-8 which is a negative photoresist frequently used. You will never get complete information of materials used to make a SU-8 photoresist because it is a trade secret which PR companies keep. They will give some name like AZ-222. You will see that in SU-8, there are 5 variants based on the number of solid used and viscosity and each has its own application. You can see the thickness and what kind of exposure should be done from illumination important point, what is soft bake time, hard bake time. and development time and how much dosage you should give. All these things are important parameters when it comes to realizing fabrication process and this is available in the table below.



SU-8 3000	% Solids	Viscosity (cSt)	Density (g/ml)
3005	50	65	1.075
3010	60.4	340	1.106
3025	72.3	4400	1.143
3035	74.4	7400	1.147
3050	75.5	12000	1.153

THICKNESS	SOFT BAKE TIME
microns	minutes @ 95°C
4 - 10	2 - 3
8 - 15	5 - 10
20 - 50	10 - 15
30 - 80	10 - 30
40 - 100	15 - 45

THICKNESS	PEB TIME (65°C)*	PEB TIME (95°C)
microns	minutes	minutes
4 - 10	1	1 - 2
8 - 15	1	2 - 4
20 - 50	1	3 - 5
30 - 80	1	3 - 5
40 - 100	1	3 - 5

THICKNESS	EXPOSURE ENERGY
microns	mJ/cm^2
4 - 10	100 - 200
8 - 15	125 - 200
20 - 50	150 - 250
30 - 80	150 - 250
40 - 100	150 - 250

	RELATIVE DOSE
Silicon	1X
Glass	1.5X
Pyrex	1.5X
Indium Tin Oxide	1.5X
Silicon Nitride	1.5 - 2X
Gold	1.5 - 2X
Aluminum	1.5 - 2X
Nickel Iron	1.5 - 2X
Copper	1.5 - 2X
Nickel	1.5 - 2X
Titanium	1.5 - 2X

THICKNESS	DEVELOPMENT TIME
microns	minutes
4 - 10	1 - 3
8 - 15	4 - 6
20 - 50	5 - 8
30 - 80	6 - 12
40 - 100	7 - 15

You can also see from 1975 to 2001, how resolution has improved and beyond that which are the important parameters. I told you that we can lower the lambda, they have lowered it from 436 to 193. Currently if I can put one more line for 2024 here, people have even gone beyond 13.5 with a different process called EUV. So, you can see how much it has decreased. Numerical aperture has significantly improved from 0.16 to 1.35 that is 8.4x and your k parameter has been changed from 1 to 0.25. So, that is around 3.5 to 4x increment. Overall whatever from around 2.7 micrometer, size has been now reduced to 40 nanometer that is 68X.

Resolution Improvement

	1975	2010	2024	Improvement
k parameter	1	0.28		3.5 X ✓
Wavelength (nm)	436	193	13.5 (EUV)	2.3 X ✓
Numerical Aperture	0.16	1.35		8.4 X ✓
Overall Resolution (nm)	2700 (2.7µ)	40		68 X

How much further smaller we can get is also a question. Foundries have successfully fabricated 2 nanometer resolution. We will discuss about these deeply in next class.
These are some of the recent progress in the last 3-4 years. IBM has successfully come up with 2 nanometer as I mentioned. Then TSMC in Taiwan have claimed 1.4 nanometer before 2 years. So, if we talk the current picture, it might be even less right. So, these are some of the improvements in the recent world, which will be discussed in detail further. If you have any question, feel free to connect with us and I will see you in the next class. Take care. Bye.