VLSI Technology
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Lecture - 24
Lithography – II

In the last class, we had discussed about optical lithography and even though optical lithography is even now the most popular lithographic techniques, it is fast reaching its limit. That is because you know the device dimensions are becoming smaller and smaller and as we have already discussed, the optical lithography the minimum resolution is just about 0.5 micron. So, when we really want to go to sub sub-micron dimensions, we have to think about other techniques and one such technique is electron beam lithography.

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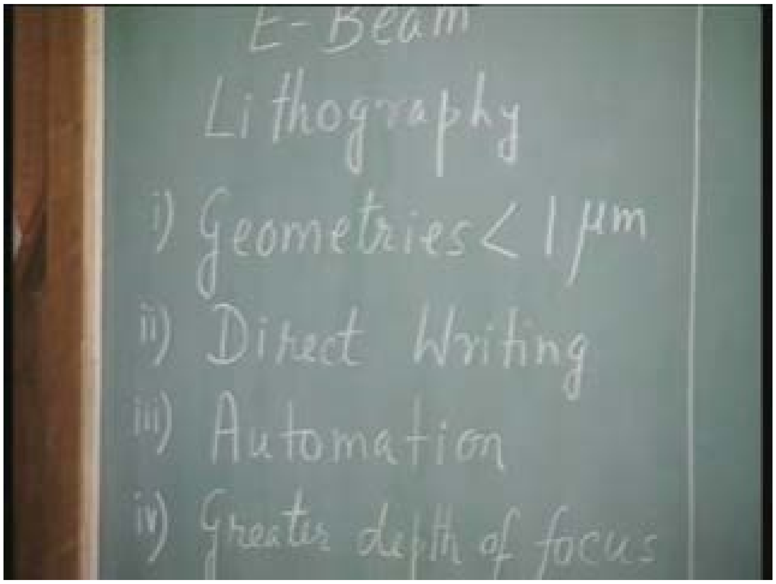

E-Beam
Lithography
i) Geometries $< 1 \mu m$
ii) Direct Writing
iii) Automation
iv) Greater depth of focus

E-beam lithography or electron beam lithography does offer various advantages. Some of them are listed here. For example, it is possible to realize geometries much less than 1 micrometer. Direct writing is also possible with electron beam lithography. By direct writing we mean that unlike in optical lithography, in e-beam lithography we do not really need any mask. It is a maskless lithography in which the pattern can be directly written on the substrate and this obviously facilitates the automation of the lithographic system. Since there is no mask there is no question of aligning with the mask and this is the most skilled job in the lithography technique - the alignment of the mask pattern on the wafer. Since in e-beam lithography we do not really have any masks, no masks are needed; therefore it can be easily automated. At the same time e-beam lithography does offer us much greater depth of focus compared to optical lithography and therefore level to level registration becomes much better. So, all these are advantages of electron beam lithography; we will come to the disadvantages later.

Let us first see now, how in e-beam lithography the pattern is written on the wafer. As the name itself suggests, in e-beam lithography we need an electron beam. The electron beam is focused; it has a diameter of 0.01 micron to 0.5 micron. It is focused on the substrate and the focused beam is scanned over the substrate; much like the electron beam is scanned in a TV screen, it is a scanned electron beam with computer control. The beam is scanned along the semiconductor surface with computer control and obviously this requires deflection and blanking at a very high frequency, at the order of megahertz.

So, what is actually done is the substrate is held, the electron beam, the focused electron beam is moved on this semiconductor substrate. Depending on the pattern that has to be written on the semiconductor substrate the electron beam is ON or OFF. If it is ON, then the e-beam resist is irradiated that changes its properties. If the focus beam is OFF, then the electron beam is not irradiating the resist. Also the substrate must be placed on a xy table, because the movement of the beam is taking place only on a very small region that is called the scan field. The scan field is of the order of 1 centimeter; 1 centimeter by 1 centimeter, whereas the substrate dimensions are usually much bigger. So, after one scan field is over, the electron beam has scanned over the entire scan field, the substrate itself is moved. That is why it is mounted on a movable xy table. It is moved and again the electron beam is scanned over the new unexposed area.

There are certain rules of thumb as far as the e-beam lithography is concerned. For example, it is very easy to understand that the resolution of the e-beam lithography will be good if the beam diameter is small. So, for very good resolution, we should have a very focused beam. The minimum feature size is actually, the rule of thumb says, the minimum feature size is actually four times the beam diameter. Therefore, if I want to really realize a say 0.1 micron resolution, then accordingly my beam diameter should be adjusted. But at the same time, if the beam diameter is very small that also affects the scan field. Usually the scan field is 2000 times the beam diameter. That means if the beam is really very narrow, then at one time the region that can be accessed by this e-beam is also very small and therefore to write on the entire substrate it takes much longer time. In fact, this is one major limitation of electron beam lithography and that is the reason why it is still not really in the main stream IC fabrication line, in spite of having so many advantages and that disadvantage is the relative slowness of e-beam lithography. The throughput is very, very small in electron beam lithography, but we will come into that later.

First of all now that we have understood how exactly e-beam lithography is taking place, let us take a look at the e-beam resist. What are the electron beam resists?

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As in case of optical lithography and photoresists, the e-beam resists can also be positive or negative depending on whether they get softened or hardened on exposure. As we already know, positive photoresists got softened when they were irradiated by UV light. Similarly positive e-beam resist gets softened when irradiated by the electron beam and negative e-beam resist gets hardened when they are irradiated by the electron beam. This is what I meant when I said that when irradiated the resist changes its properties.

Now, electron beam resists are also organic materials. They are basically organic polymers and upon irradiation either of the two things can happen. That is either the molecule of the polymer can break that is called chemical bond breaking or else they can form more bigger molecules by crosslinking, making a three dimensional structure. Now, if these organic molecules, the monomer chains, they crosslink and become bigger molecular chains, then obviously the molecular weight is going to increase and once the molecular weight increases, it becomes more difficult to dissolve them in the developer solution. So, that is what we meant that negative photoresists hardens on irradiation. Upon irradiation, crosslinkage of monomer chains are taking place and therefore, molecular weight is increasing. Therefore, it is more difficult to be dissolved; therefore the negative photoresist is getting hardened on irradiation. On the other hand in case of positive e-beam resist, chemical bond breaking is taking place. The chains are breaking, the molecular weight is reducing and therefore it is easier to dissolve them in the developer solution and therefore positive photoresist, positive e-beam resists are softened upon irradiation.

There are advantages and disadvantages in both cases. For example, if we take negative electron beam resists, because of crosslinking they are more difficult to dissolve. But when we soak such an e-beam coated, such an e-beam resist coated substrate into the developer solution the resist is going to absorb the developer solution and upon absorption, the resist is going to swell and because the resist is going to swell it is actually blurring the features a little bit. On the sides there is a swelling taking place and therefore the minimum feature size gets slightly distorted. Therefore, negative e-beam resists is going to offer poor resolution.

On the other hand, there is no such problem with positive e-beam resist. It gets softened and therefore it is easy to remove in developer solution. So there is no problem of resolution; resolution is better with positive e-beam resist. But, in order that the positive e-beam resist is completely dissolved in the developer solution, it must be ensured that all the layers of the e-beam resist has absorbed the e-beam and chemical bond breaking has taken place. Only then, this e-beam resist will get dissolved in the developer solution. Therefore, in general, the positive e-beam resist has to be exposed to the e-beam for a much longer time. This is what we mean by poor sensitivity. That is they are not so sensitive to the e-beam. In order to change their property, it has to be exposed to the e-beam for a much longer time and that obviously makes the throughput much less. So on one hand, positive e-beam resist is going to offer us better resolution but lower throughput and negative e-beam resist is going to offer us comparatively faster throughput, but the resolution is going to be poor. So, depending on the application, one has to choose either positive or negative e-beam resist.

Let us now take a look at the problems associated with the electron beam lithography. The first problem with electron beam lithography is of course the slowness. Because it offers direct writing, the e-beam has to be scanned over the entire substrate and then again you have already seen that if you are using positive e-beam resist it has to be exposed to the e-beam radiation for considerable amount of time and that really pulls down the throughput of the process. Apart from the throughput problem, there is another problem known as the proximity effect.

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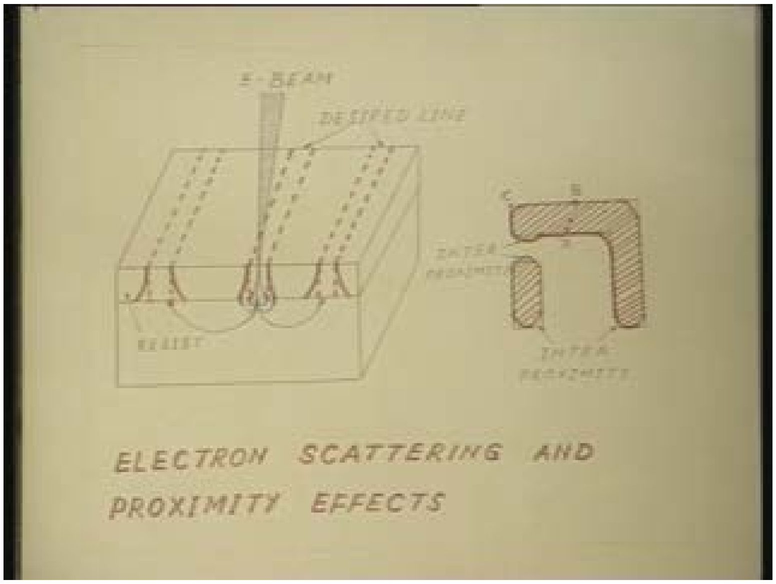

ELECTRON SCATTERING AND PROXIMITY EFFECTS

If you look at the first figure then we can see what this proximity effect is all about. In this we are actually showing a substrate surface which is coated by e-beam resist. This is the focused e-beam on the substrate surface and the red dashed lines, the region bounded by the red dashed line, shows the pattern that has to be realized on the substrate. Obviously the region bounded by the red dashed line is what we desire; what we desire to obtain, the pattern that we want to obtain on the substrate surface.

Now, what is happening is this. As the e-beam is focused on to this, there is going to be considerable scattering of the electrons and the scattered electrons, around the curved path actually shows the scattered electrons, the scattered electrons can actually go quite a large distance away from the original pattern and this will therefore cause broadening of the actual feature size as has been shown by the red solid line here. See, the red dashed line signifies the actual pattern that was desired to be obtained and this curved lines show the actual, the real pattern that we are going to obtain on the semiconductor substrate. This is called proximity effect. Proximity basically means being nearby. So, you can see that, because this pattern was near this pattern, the scattered electrons have come all the way to this next pattern and this has caused the broadening of the actual pattern.

It will become clearer it if you take a look at this segment of the figure.

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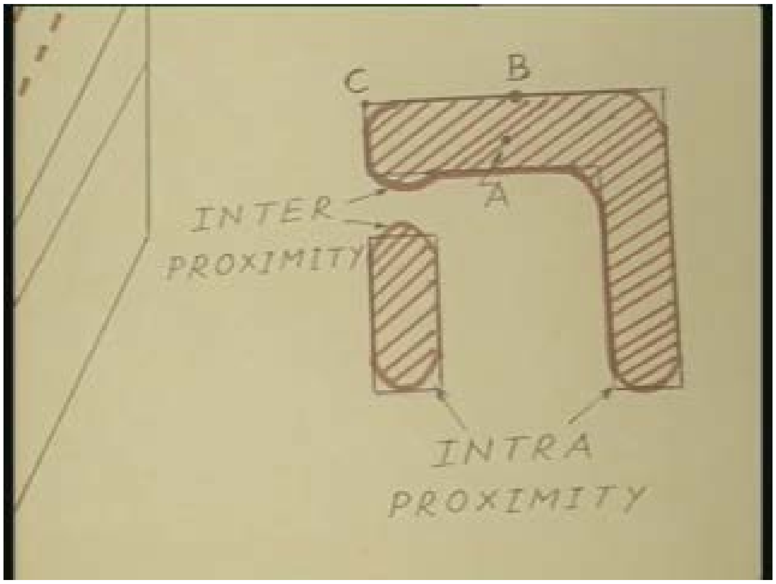

I have shown here some pattern that is to be realized on the semiconductor substrate. It consists of one L shaped pattern and one rectangular region. Let us take three points in this L shaped pattern - point A, point B and point C. You see, all the points surrounding A must also be exposed to the e-beam irradiation. Therefore point A is actually receiving the maximum benefit of the e-beam radiation. Compare this with point B. Only points which are lying on this side of point B, they receive the e-beam irradiation whereas all the points lying on the other side of point B, they do not receive the e-beam radiation. Therefore in effect, point B is receiving only half of the total e-beam radiation that is received by point A. Point C is of course at a still more disadvantageous position. Point C is at one corner and therefore compared to point A, it is receiving only one fourth of the total e-beam radiation. Therefore you see, the amount of e-beam radiation received by different points on a pattern is not the same.

Usually it is adjusted for point B. That is the e-beam radiation time is adjusted such that point B is fully developed. But, when we ensure that point B is fully developed, chances are that point C will not be fully developed and therefore instead of realizing the actual L shape, we would have a curved corner like this. Point C will not really be fully developed and therefore the pattern will look like this, curved. This is called the intra proximity effect, the intra proximity effect as can be seen at this corner also. Basically the intra proximity effect means that because of insufficient radiation at the corners, the corners do not get fully developed. On the other hand, because this rectangle is placed close to this L shaped pattern, the points here are receiving more than its quota of radiation. The electrons which are scattered from here on to this like here, the electrons which are scattered to the next pattern it is causing an over development and therefore the pattern has actually taken the shape that is shown here. This is called the inter proximity effect. So, we have seen both the intra proximity effect as well as the inter proximity effect.

Essentially this means that the different points, different portions in the pattern they receive different quota of e-beam radiation and therefore they develop differently. In other words, due to proximity effects, different portions of the substrate have to be exposed to e-beam radiation for different amounts of time. Usually the developing is done till the width of the pattern corresponds to the design and therefore the corners are slightly under exposed. This proximity effect is actually a major limitation in e-beam lithography, particularly so when we have closely spaced patterns and that is bound to be the case as the device dimensions becomes smaller, because as you know when the device dimensions are smaller we have more devices packed close together, therefore more patterns packed close together and therefore they are going to affect the resolution.

So, these are the two major limitations of the electron beam lithography. One is the proximity effect and other is the throughput and because of this, as I said electron beam lithography is still not considered to be the most viable option in VLSI technology. Instead, e-beam lithography is primarily used for writing patterns on the mask plate itself. Because, for realizing thousands of devices, we need to have only one mask plate, so the throughput is not of very major concern in this case. By e-beam lithography, we can usually write about one mask plate per hour; that is fine. That is the time constraint is not so significant here, therefore the e-beam lithography is primarily used in order to generate these patterns on the mask plate and then, from the mask plate to the substrate it is any of the other standard techniques. So, so far we have seen the optical lithography and the e-beam lithography. In optical beam lithography the resolution is of concern, in e-beam lithography the throughput is the major concern.

So, now we are going to talk about a third lithographic process that is the X-ray lithography, where we try to bring the best of optical lithography as well as e-beam lithography.

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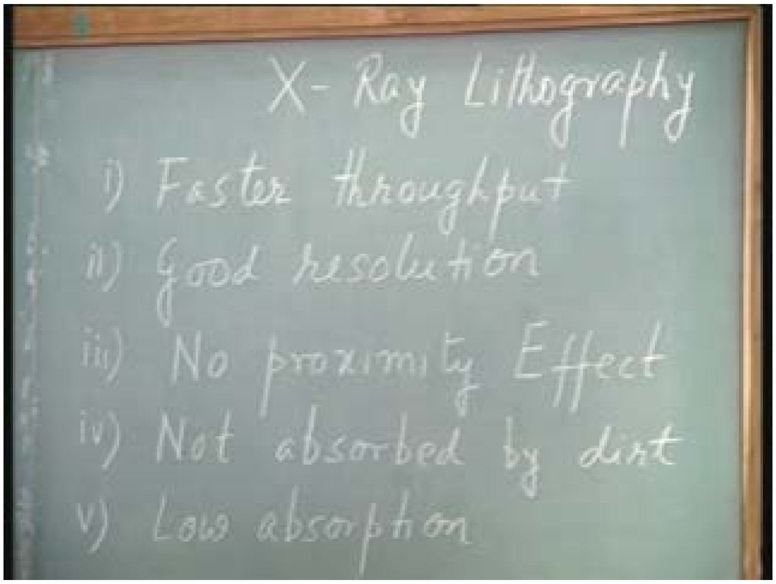

X- Ray Lithography

i) Faster throughput
ii) Good resolution
iii) No proximity Effect
iv) Not absorbed by dirt
v) Low absorption

So, the third lithographic technique that we are going to discuss is the X-ray lithography. Essentially I would say that the X-ray lithography is an extension of the optical lithography, in the sense that the principle involved is very much the same. Only difference, only major difference is that instead of UV light, in this case we use X-ray to irradiate the resist. Unlike electron beam lithography, in X-ray lithography we cannot do a direct writing. So, like optical lithography here we need a mask. Usually X-ray lithography is done by using proximity printing process. Proximity printing means that the mask and the substrate and brought close together, but they are not actually in contact. The typical separation between the mask and wafer is of the order of 40 to 50 microns, 40 to 50 micrometer.

So, X-ray lithography does offer us quite a lot of advantages. The major advantage compared to e-beam lithography is of course the faster throughput and because we are using X-rays that is with much smaller wavelength, the resolution is also good, much better than that in case of optical lithography and since the electrons, the secondary electrons generated by X-rays do not have such high energy, therefore the proximity effect as we have seen in case of electron beam lithography is also not present here. Moreover X-ray is not absorbed by dirt, so the presence of dirt on the mask plate does not really materially affect the pattern generation. At the same time the X-ray has low absorption in the resist and that also helps in the sense that the exposure is uniform and therefore we can get straight-walled feature.

Basically the X-ray lithography as I said, it is an extension of optical lithography proximity printing. So, what is done in case of X-ray lithography is like this; this system has an e-beam focused on a water cooled palladium target. When the e-beam is focused on this water cooled palladium target, it generates X-rays. The wave length of these X-rays is 4.37 Angstrom. This smaller wavelength helps in achieving much better resolution in X-ray lithography compared to the optical lithographic process. These X-rays are generated and passed through a beryllium window into a chamber. This chamber is filled with helium. Helium is preferred because it will not absorb the X-rays. Inside this chamber the mask and the substrate are placed close together, but not in actual contact. The separation between the two is about 40 micron as I have already told you and here the X-ray is used to develop the mask pattern on the substrate. The X-ray mask is usually in the form of thin membrane coated with gold.

The thin membrane material can be a lot of things; it can be polyamide, it can be silicon, it can be aluminum oxide, it can be silicon nitride. It is essentially in the form of a thin membrane, which will allow the X-rays to pass through it and the top surface of this thin membrane is patterned with gold. Gold is normally used as the X-ray absorber material. So, the regions which are coated with gold it will not allow the X-ray to pass through. The regions which do not have the gold pattern will allow the X-rays to pass through and this is how the pattern will be written on the semiconductor substrate and as far as X-ray resists are concerned, well, all electron beam resists can be used also as X-ray resists. One of the very common examples is PMMA or poly methyl methacrylate. PMMA is a very common resist which is used both in electron beam lithography as well as in X-ray lithography. But, it does not mean that the X-ray lithography does not have any problem. The major problem in X-ray lithography comes from geometric effects.

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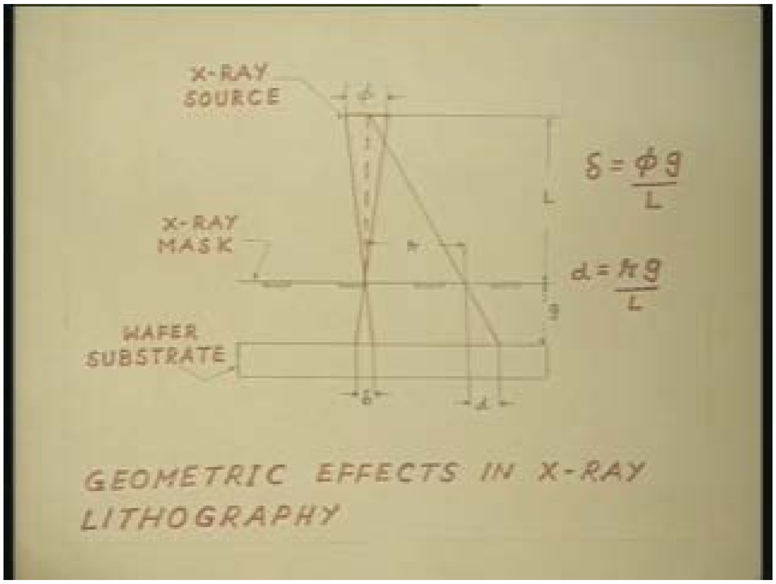

GEOMETRIC EFFECTS IN X-RAY LITHOGRAPHY

The geometrical effects pose the limitation in the X-ray lithography process as we can see from this figure. Now in this figure, we are actually showing the cross sectional view of the wafer substrate and this is the X-ray mask which is separated from the wafer substrate by a distance g, which I told you is of the order of about 40 micron and this is the X-ray source. It has X-ray beam of diameter 5. Now you see, these are the patterns on the mask. So, at the edge of the mask pattern, if we look at the focus, the X-ray beam is focused at the edge of the mask and because of the finite separation between the mask and the wafer substrate, it causes a penumbral blur on the substrate. Instead of getting the image as a point, we obtain a blur, a penumbral blur of dimension of the order of delta and it can be shown from geometrical consideration that this amount of penumbral blur, delta is dependent on the separation of the mask and the wafer, it is dependent on L that is the distance of the X-ray source from the mask as well as on the X-ray beam diameter. So, delta is given by phi g by L. In actual case this delta could be of the order of 0.05 micron, 0.02 to 0.05 micron. So, this is one problem with X-ray lithography.

The other problem is as we move away from the center of the mask look at the patterns which are situated far away from the center. This is how the X-ray beam is coming on the sides and finally when it reaches the substrate surface, the distance has actually got slightly modified. If we look at the pattern which is situated R distance away from the center, then we see that the actual pattern on the semiconductor surface has actually got shifted by an additional amount of d and this d obviously is going to depend on how far away from the center of the mask the pattern is located. That is d is going to be directly proportional to r and obviously it is going to depend on the separation between the mask and the substrate that means g is again coming into picture. So, you can see that the amount by which a pattern gets shifted on the semiconductor surface is given by r times g by L. So we see that for both delta as well as d, the factor g by L is actually a very important parameter, where g is the separation between the mask and the substrate and L is the distance of the X-ray source from the mask and in order to keep the geometrical effects to a minimum, this g by L should be as small as possible.

Usually however, the problem of these geometrical effects are taken care of in the mask itself. That is as we move away from the center of the mask the separation between the patterns is slightly reduced, so that on the semiconductor surface they all appear to be equidistant. So, X-ray lithography does offer a lot of advantages compared to both optical lithography as well as e-beam lithography. It scores over the optical lithography by virtue of the smaller wavelength of radiation that is used. Because, you know in case of optical lithography the final limitation comes about because of the diffraction effects and that is related to the light wavelength that is being used.

In case of X-ray lithography since the X-ray wavelength is much smaller, the resolution is comparatively better. At the same time, the X-ray lithography is much faster than the e-beam lithographic process. It is actually as fast as the optical lithographic process and therefore the throughput is much better and X-ray lithography can actually be used in the

IC production. At this present moment it is very difficult to say which one is going to be the lithographic technique of the future.

On one hand in case of optical lithography efforts are on to go for deeper and deeper UV. That is same principle, reducing the wave length of the light that is used therefore to make the resolution much better. On the other hand, efforts are also on to make the electron beam lithography a faster process, not sacrificing the resolution, but making it a faster process and of course, the third choice that is the X-ray lithography which combines many of the positive features of both optical as well as e-beam lithography. Along with these, there are also other lithographic techniques which are being talked about, for example ion beam lithography. Ion beam lithography is essentially the same as electron beam lithography. Only instead of an electron beam, an ion beam is used and since ions scatter much less than electrons, the proximity effects as we have seen in case of electron beam lithography is going to be much less in ion beam lithography compared to the e-beam lithographic process. So, essentially these are the three classes of lithographic process.

So, by lithography, to summarize, by lithography therefore we have seen that a pattern can be written on the semiconductor surface. In order to generate this pattern on the semiconductor surface, we usually need a mask. A mask is nothing but the master plate on which this pattern is generated. From this mask this pattern is transferred on to the semiconductor surface. In doing so, we have to coat the semiconductor surface with a resist material which is sensitive to the type of radiation that is being used. According to the type of the resist, we can call it either a positive resist or a negative resist. A positive resist gets softened when irradiated; a negative resist gets hardened when irradiated. So, through the mask the irradiation hits the resist coated surface and therefore accordingly modifies the property of the resist. One notable exception is of course the electron beam lithography where you do not need a mask, instead the electron beam is focused directly upon the resist coated substrate and it is switched ON and OFF at a very fast rate by, usually by computer control. So, this causes the property of the resist to change so that in the developer solution, after irradiation when the substrate is put in the developer solution from certain regions the resist goes away and then once the resist has got patterned on the semiconductor surface, usually the next stage is chemical etching.

After lithography what we have realized is a pattern on the resist. That is some portions on the semiconductor surface is protected by the resist and other portions are exposed. Usual practice is now this semiconductor is etched either by using a chemical solution which is called wet etching or sometimes by subjecting it to plasma that is called dry etching. But, whatever be the process, the actual process of etching, basically what is done is now the unprotected regions of the semiconductor is getting etched and the etching is the topic we are going to discuss in the next class.