VLSI Technology
Dr. Nandita Dasgupta
Department of Electrical Engineering
Indian Institute of Technology, Madras

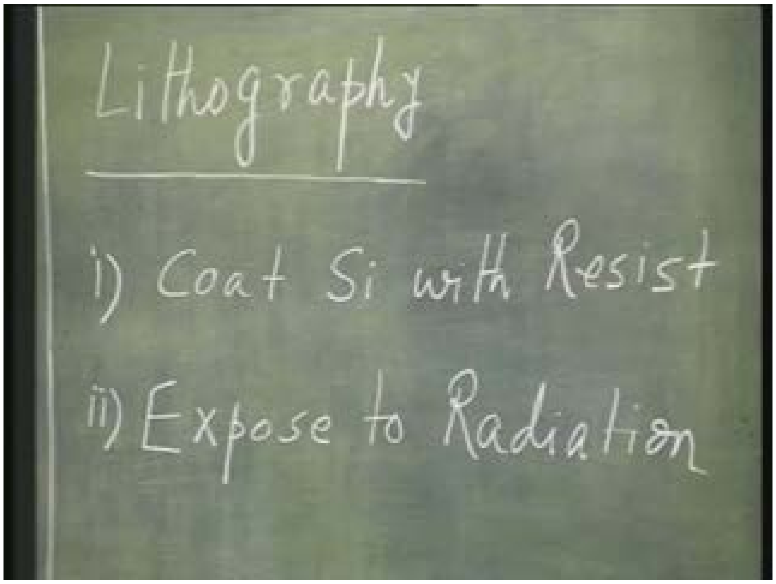
Lecture - 23
Lithography - I

You are now quite familiar with the different doping techniques in VLSI technology. That is you know, how by diffusion or by ion implantation we can selectively dope the silicon; you can put controlled amount of impurity, how can we control the peak concentration, the surface concentration, the junction depth and how to evaluate the properties of the doped region. But, in all these discussion, there was one implicit assumption that is ion doping selected regions in the semiconductor only. We have not yet discussed how do we select these regions? These regions where the dopants have to be incorporated is selected and marked by the process called lithography; lithography or sometimes referred to as photolithography. Lithography or photolithography is the process of transferring geometrical patterns from a mask to the silicon wafer. That is I have a mask in which the geometrical patterns are already present and they transfer these geometrical patterns from the mask on to the silicon wafer. This is called lithography.

Actually the concept is very old, more than 200 years old, when a pattern, at that time there was no silicon wafer, there was no concept of photolithography, but the concept of transferring the pattern was still there and in that case one used a stone plate on which the pattern was engraved, you know and you put some ink or something on to that engraved pattern and then press it down on to your paper or wherever you want to transfer the pattern, so the ink stained portion will leave its mark on the material. So, that was the first concept of lithography. In fact, lithos actually means a stone; stone plate that is a lithos. From there this term has been coined – lithography. In VLSI parlance of course, lithography in general means a combination of a few steps. The idea is to transfer some pattern from the mask to the silicon wafer.

How do we do that? First of all we start with coating the silicon wafer with a radiation sensitive polymer film called the resist or the photoresist, sometimes.

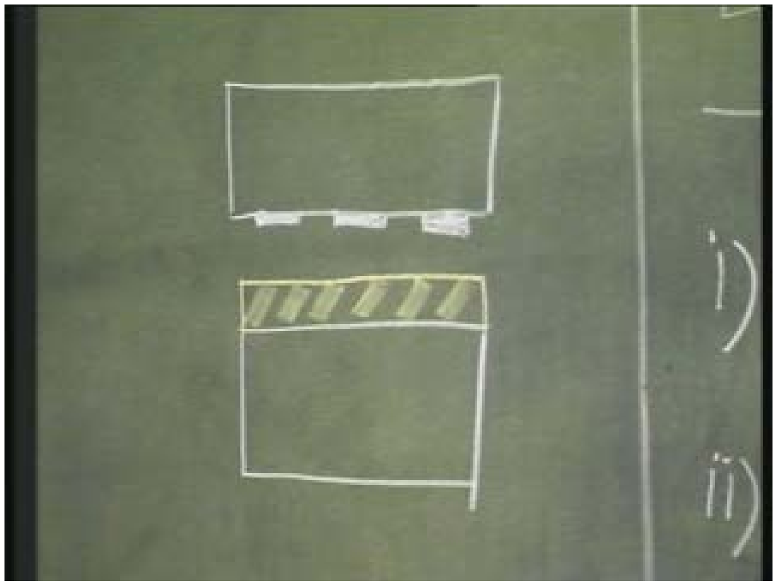
(Refer Slide Time: 4:41)



So, step number one coat silicon with resist. Resist is nothing but a radiation sensitive polymer. What do I mean by a radiation sensitive polymer? That is when it is exposed to a particular type of radiation, its properties change. That is all I am going to say at the present moment, its properties change. How it changes, we will come to it a little later. So, generally this polymer is available in a liquid, a viscous liquid form. So, what you do? You take one or two drops of this viscous liquid, put it on the silicon wafer and then very quickly spin the wafer; hold it in a vacuum chuck and then spin it very fast say, at 4000 rpm or so, so that you have a thin uniform coating of this resist film on the wafer, right.

I take a few drops of this resist in a syringe, put it - one or two drops on the silicon wafer, then hold this silicon wafer with this one or two drops of resist on it in the vacuum chuck and then spin it at a high speed, very quickly, so that I have a uniform layer of resist on top of the silicon. By varying the spinner speed, I can adjust the thickness of the layer. That is my first step. Second step is now I expose this resist coated wafer to proper radiation that is to the radiation to which this resist film is sensitive; expose to radiation. Now, this exposure may or may not be through a mask. Most cases however it is through a mask that is you have coated the silicon wafer with the resist. What you have is something like this.

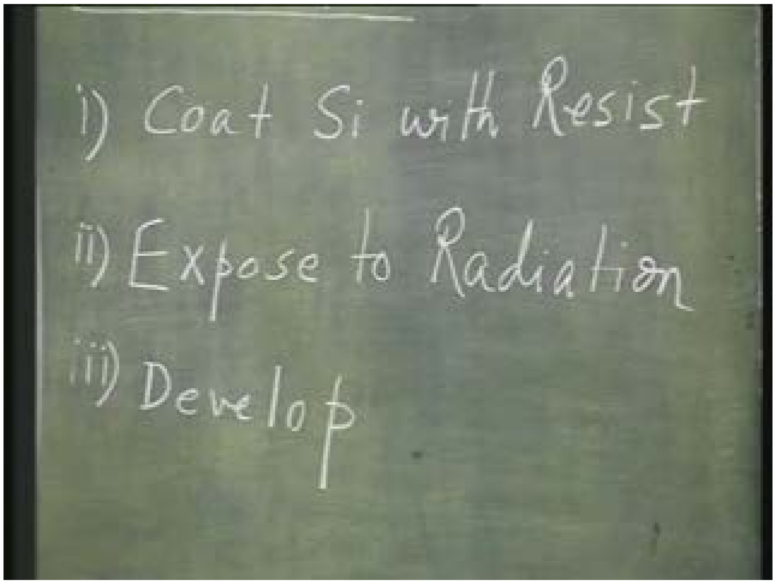
(Refer Slide Time: 7:34)



I am looking at the cross sectional view. I have a layer of photoresist on top of the silicon wafer and now I have a mask with the proper geometric pattern on that. What do I mean by this? That is some parts of the mask is opaque and some parts is transparent. These are the portions which are opaque to the radiation. A mask plate is nothing but a glass plate with this transparent and opaque regions, delineated in it. So, now you allow the radiations to fall onto the wafer through the mask. So, what happens?

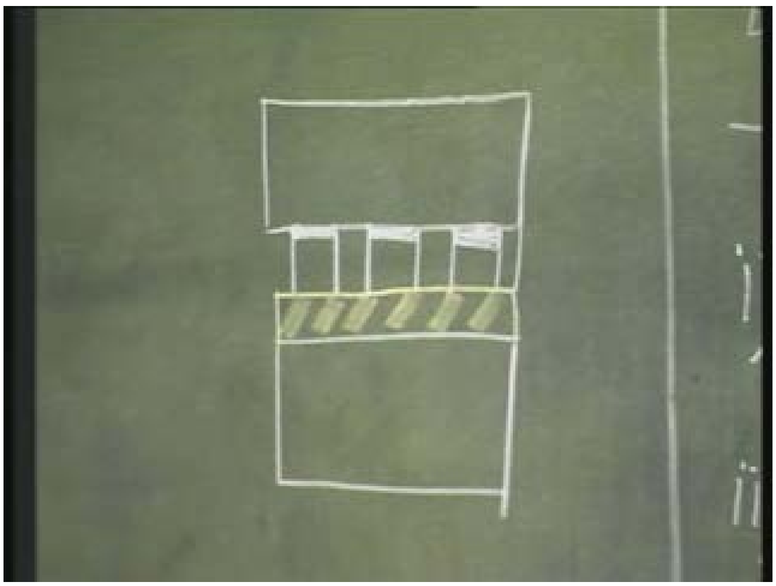
Only those regions of the mask which are transparent to the radiation allows the radiation to fall on the semiconductor. Now you see, I told you that the resist is radiation sensitive. So, only those portions which are exposed to the radiation, their properties are going to change. In some cases they might get softened; the exposed region might get softened, easier to remove. In some cases, the exposed region might get hardened, difficult to remove, depending on the type of resist I have. So, you expose it; the exposed photoresist or the exposed resist have changed their properties.

(Refer Slide Time: 10:17)



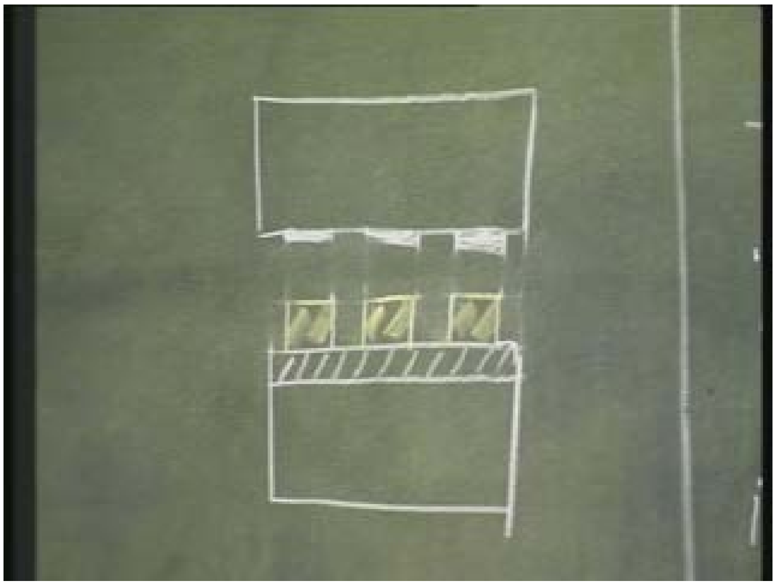
Now I come to step number 3. This wafer is now soaked in a developer solution. We call it developing. I have already told you that the exposed resist has its properties changed. Suppose the exposed portion have become soft, easy to remove, then what is going to happen?

(Refer Slide Time: 10:54)



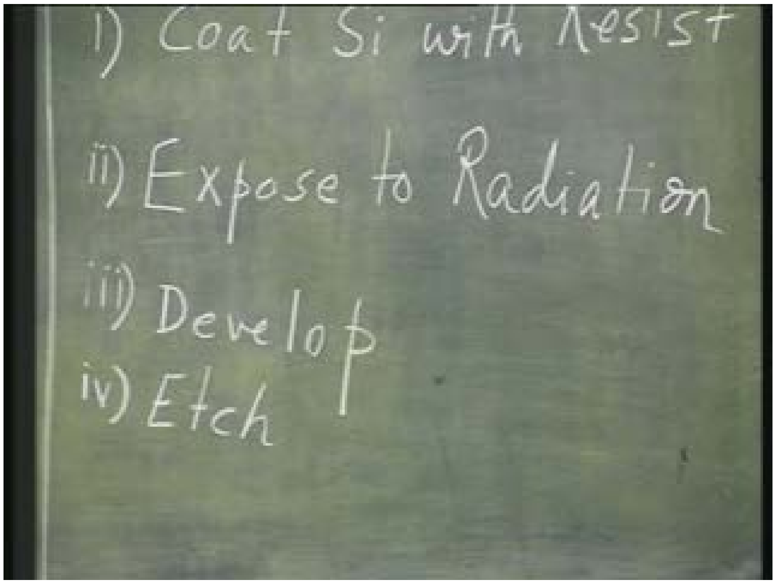
This is the portion which is exposed to the radiation, again this is the portion which is exposed to radiation, this is the portion which is exposed to radiation and this is the portion which is exposed to radiation. The photoresist directly underneath this is exposed to radiation and now it has become soft, it is easy to remove.

(Refer Slide Time: 11:34)



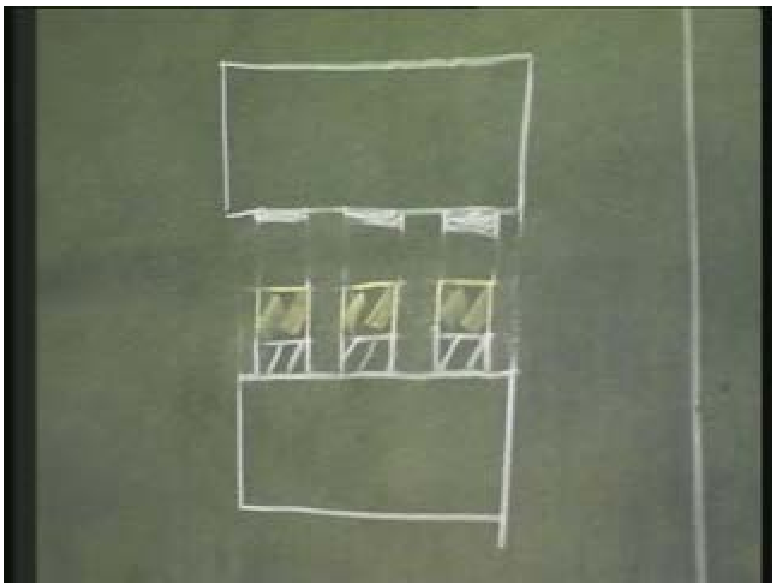
So, when I put it in the developer solution, these portions go away, leaving me with resistance only in the unexposed regions. Do you see? So now, I have transferred the pattern from the mask on to the resist on top of the silicon wafer, agreed. Now, in most cases this wafer will have an oxide on its surface, on the surface on which we coated the resist that is generally the oxidized surface. So, this is actually silicon dioxide, this is the underlying silicon and on top of that I have now the pattern in photoresist after developing it. Now, what do I do? I put it in diluted HF; etching that is the fourth step.

(Refer Slide Time: 12:47)



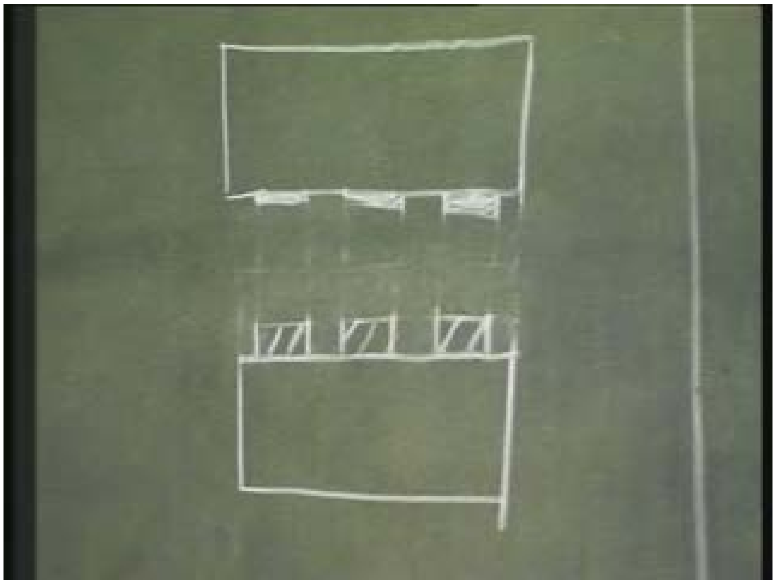
What do you see here? Photoresist is protecting certain regions of the oxide and certain other regions, from where the resist is removed is now exposed.

(Refer Slide Time: 13:15)



So, when I put it in diluted HF solution, from these portions the oxide will get etched, so that what I have is something like this, right. Now, let me remove all the photoresist in a photoresist removal solution.

(Refer Slide Time: 13:56)

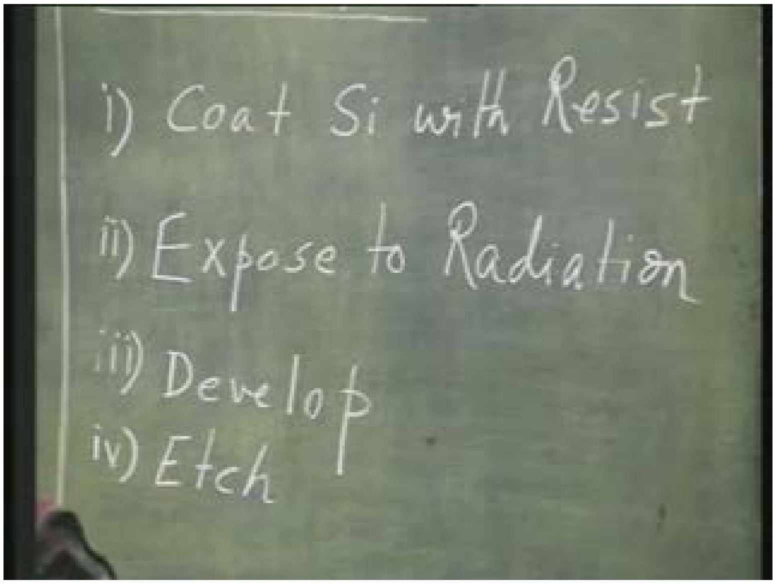


The purpose of the photoresist is achieved. Now, I can remove the resist. What do you see? What do you see here? Compare the pattern on the mask with the pattern on the oxide. What do you see? The opaque regions in the mask they have, corresponding to that I have oxide sitting on the wafer; the transparent regions in the mask corresponding to that I have no oxide. So now, if I dope the semiconductor which are the regions where the dopants will get incorporated? The regions corresponding to the transparent portions of the mask. In other words, these windows are the windows I have opened in the oxide. The pattern on the semiconductor corresponds, one is to one correspondence to the mask pattern. So, this type of resist is called a positive resist. The pattern of the mask and the pattern on the semiconductor is identical. This is a positive resist, where the exposed resist gets softened.

I could have another type of a resist. That is the resist could have got hard in the regions where it is exposed to the radiation and in that case what would I have? I would have a compliment of the mask pattern etched on the semiconductor. In other words, I will have a negative of the mask plate. This is called a negative resist. So, a positive resist is one which gets softened when it is exposed to radiation and a negative resist is one which gets hardened when it is exposed to radiation.

So, you see, what are the things now we have seen?

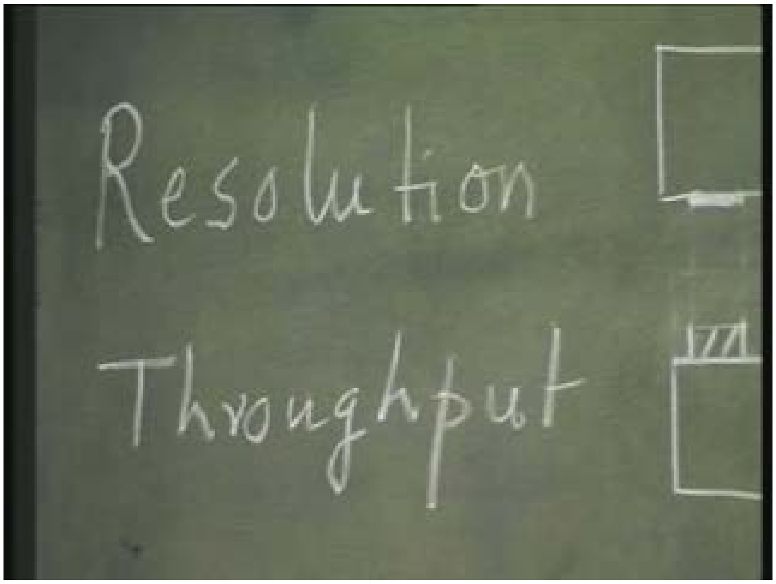
(Refer Slide Time: 16:39)



We have seen that there are four basic steps in a lithography process, which consists of coating the resist on to the wafer and exposing the resist coated wafer to proper radiation and then developing the wafer and finally etching and at the end of it, I have the required pattern on the semiconductor. I told you that I may or may not need the mask. But for most of our applications today, we need a mask. The only difference is when you do e-beam lithography, electron beam lithography. Then you can, you have the resist coated wafer and you can focus the electron beam directly on this resist coated wafer, so that direct writing is possible. You can control the beam that is the beam will or will not fall on particular regions; you can blank the beam wherever you do not want radiation to take place. So, in that case you do not need a mask, so we say electron beam is one lithography technique where we do not need a mask as direct writing is possible.

Before I go on to define what other types of lithography, like for example, I just said electron beam lithography, it is one type of lithography; before I go on to define what the different types of lithography we have are, let me talk about some figures of merit for a particular lithography process. How good or how bad the lithography process is figures of merit.

(Refer Slide Time: 18:31)

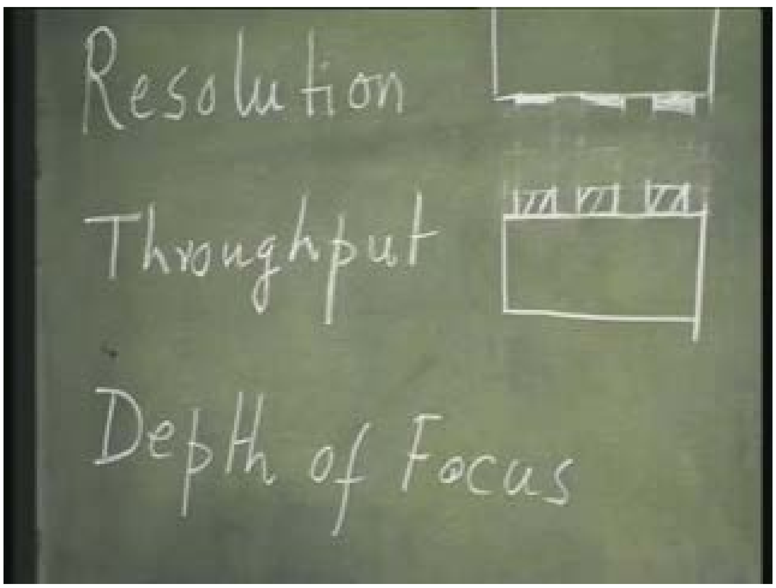


So, the two main figures of merit in a lithographic process is its resolution and its throughput. Resolution obviously means what is the minimum feature size. I will go one step further and say resolution actually means that if I have a feature size in the mask say, 1 micron feature size in the mask, does it stay 1 micron in the silicon wafer or does it become say, 1.2 micron or 0.8 micron that is whether it increases or decreases, how good is the resolution that is how close to the mask it is. So, resolution does not only mean the minimum feature size, it also means the precision with which the minimum feature size can be incorporated. You see, if your feature size is 10 micron, then obviously it does not matter whether it is 10 micron or 10.2 micron. But, if it is 1 micron, then it matters. Then it becomes 20% variation. So, the smaller your minimum feature size is the greater is the need of having it very accurate. They are sort of interrelated together, the minimum feature size as well as the accuracy with which the minimum feature size can be transferred to silicon wafer. That is a very important feature, resolution.

Second important figures of merit that is the throughput that is also no less important. Throughput means how many wafers can be processed in a given time and you know, as engineers we all know, that the bottom line is cost. How cost effective your product is. I have to sell the product finally. I cannot afford to have a very expensive system even if it is very good, because I will not have any prospective buyers. It is also important to have the wafer processed in a given time that is the throughput. How many wafers can be processed in one hour? For example, electron beam lithography has many advantages, but it loses out on this one count – it is a very slow process. We will discuss more about it when we discuss the individual lithography.

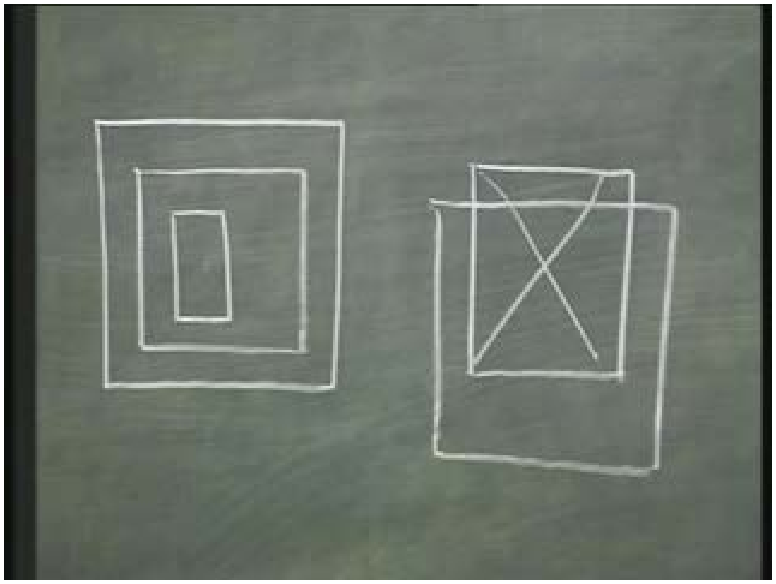
These two figures of merit are very easy to understand. There is also a third figure of merit which is called the depth of focus.

(Refer Slide Time: 21:24)



Please understand that in any VLSI process, you will have a large number of mask steps, 6 or 7 mask steps at least. For a bipolar junction transistor for example, first of all I must have my active area masked. Then I must have my junction isolation masked, then I must have my base diffusion masked, then I must have my emitter diffusion masked, then I must have my contact metal masked; like that, right and all these masks must be aligned to each other. What do I mean?

(Refer Slide Time: 22:16)

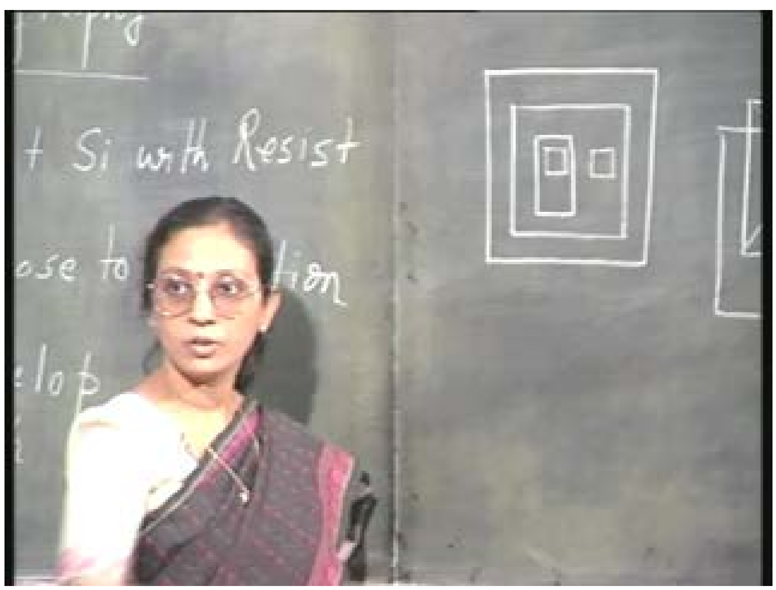


That is if this is my active area mask, my isolation mask must be exactly surrounding this. This is my first mask, this is my second mask. The second mask must be aligned to this. If however I have pulled it down, I cannot have it, right. I must ensure that mask number two is aligned to mask number one. Similarly my base diffusion mask must come inside the active region and should not spill over to the adjacent regions, agreed. So, all these masks must be aligned to each other. How do I ensure this alignment?

I have first of all carried out the active area definition, I have carried out the buried layer implantation or diffusion. Then, I have followed it up with epitaxy. If you remember, I said that there will be an indentation on the wafer. So, now my junction isolation mask must be aligned with respect to this indentation. That is this low level indentation means I have a step on the wafer surface. So, that second mask must be aligned with respect to the steps; surrounding that step I must have my second mask, agreed. So, now you understand that this depth of focus concept is very useful. I therefore must be able to see at two different levels. That is on the surface where my second level of masking is and below that where the indentation is. The indentation means I have a vertical height, so my depth of focus all those who are familiar with camera, you know that you call a camera a good camera if I can focus on the first row, but does not let it go out of focus in the second or third row; depth of focus. Otherwise, I will have only ………. focused and rest of all, you will all be a blur. I do not want that. I want to focus on everybody. So, I must have a good camera which can have a good depth of focus. Same thing in photolithography; photolithography is very close to a photography, I must have a good depth of focus. If I have a good depth of focus, alignment becomes easier, life is much simpler. So, these are the three principle figures of merit in any lithography process.

Before going on to the actual lithographic process, let me tell you a little bit about mask making and then will come to the lithography process. How does one make the mask? First of all, like I started to do for this bipolar junction transistor you complete the composite mask drawing.

(Refer Slide Time: 26:00)



That is you see, I have defined the active area, I have defined the junction isolation, I have the base diffusion, now, I must have the emitter and the collector pocket and then the contact metallization, etc. So first, this is my first step. I prepare a composite set of masks; how they should be with respect to each other that is where the junction isolation should fall with respect to the active area, where the base diffusion should fall with respect to the active area, where the emitter diffusion should fall with respect to the base diffusion and like that. Then, this is your first step in mask making. Then, you break it up in individual mask drawings. That is I have one drawing for the active area definition, I have another drawing for the junction isolation definition, I have a third drawing for the base diffusion, a fourth drawing for the emitter diffusion that is in each level whatever feature I have to define that is one set of mask and I really blow it up; I do it in a very large scale, you know, 100 to 2000 magnification, very large scale; you really blow it up and do it on a very big scale.

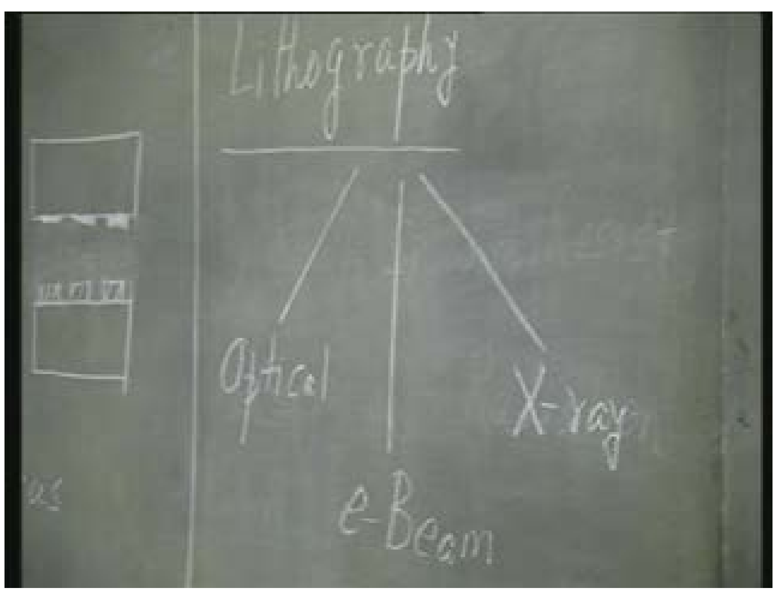
All I am doing remember is just for this one transistor. Then I could have a step and repeat. That is the same mask pattern can be replicated a number of times to give me my hundred thousand transistors on a given chip. I am talking about just simple discrete transistors. You want to have a circuit, what you should have is the minimum block. You know, in VLSI design this is how we design, right. We first design a minimum block and then allow it to get replicated. So, this minimum block you define, you make a set of composite mask and then break it in so many levels of mask 100 to 2000 magnification and then, you photographically reduce it to a magnification of 10 and put it on a glass retical. Then you can have one more reduction to have it in a one to one feature size and then put it on the photosensitive glass plate.

But, this will work only when I have a very simple mask design, for example, just a set of discrete transistors, then I can employ this. Whenever I have a circuit, even a moderately complicated circuit, this is going to be extremely difficult. So, we have a set of CAD tools. For example, in university level we use magic; more complicated, we use cadence. These are your CAD tools by which you can design the masks. Then, the output of this magic file that is stored on a magnetic tape and then you can carry the magnetic tape to the people, for example BEL, who have a pattern generator and feed it there, from the magnetic tape on to the pattern generator and the pattern will be generated. That is the pattern will be put on a photosensitive glass plate.

Now, here again I have the problem of the minimum feature size. If your feature size is up to 5 micron, minimum feature size is up to 5 microns, then you can have an emulsion coated glass plate. If your feature size is less than that, then the emulsion coated glass plate will not do, then we must have a chrome plated glass plate. That is the opaque portions are marked by putting chromium on the glass. You know how it is done? You put chromium on the glass plate and then selectively etch it away from the regions where you want to make it transparent. So, a chrome plated mask will have much better resolution. If you have a minimum feature size of less than 5 micron, then you should use a chrome mask. So, use either an emulsion mask or a chrome mask. Emulsion mask if your feature size is relatively conservative, up to 5 microns; chrome mask if your feature size is less than that. Needless to say a chrome mask is going to cost almost double the amount of the emulsion mask; you pay some, you get some. So, this is the basic idea of how to make a mask.

Now, we come to the types of lithography. The process of lithography is classified according to the type of radiation. That is one type of classification. Depending on the type of radiation we use, the lithography is called an optical lithography, an e-beam lithography or an X-ray lithography.

(Refer Slide Time: 32:11)

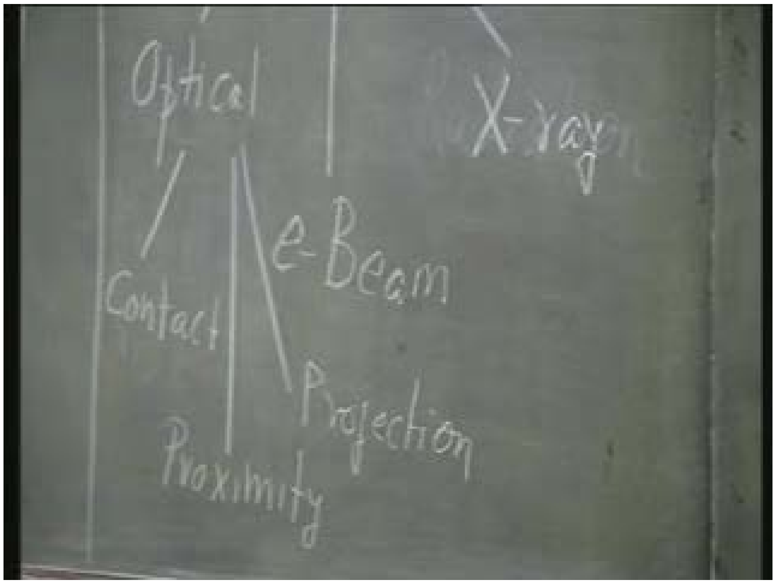


It can be optical lithography or e-beam lithography or X-ray lithography. In optical lithography, the resist is called a photoresist which is sensitive to light and the light that we use is UV light. In e-beam lithography, the resist is called an e-beam resist that is it is sensitive to electron beam radiation. In this case, as I said we do not need a mask, direct writing is possible by simply using the e-beam like a pen. You know, I can just focus that e-beam and write that is scan on the wafer surface. Blank the beam in the regions I do not want the resist to be exposed to the beam and X-ray lithography is basically nothing but optical lithography, only instead of UV light, we are going to use X-ray. This is one set of classification.

I have already told you that the resist can be positive or negative; positive when it gets softened on exposure, negative when it gets hardened on exposure. The particular chemical material we use is going to be different for different types of lithography. But, the basic aspect remains the same. All resists, no matter whether it is a photoresist or an e-beam resist or an X-ray resist, will be called positive if it is softened on exposure to that particular radiation and will be called negative when it is hardened on exposure to that particular radiation. So, positive and negative resists and then of course, the first question that comes to the mind is what do you actually use - optical or e-beam or X-ray? That is where you need to see the relative performance, relative merits and demerits. We will start with the optical lithography, because even now, even today that remains as the most popular technique of lithography and it is obviously the oldest technology.

In optical lithography, the steps I have already outlined to you; it follows these four basic steps. The radiation that we use is UV light. So, I can further classify this optical lithography as contact printing, proximity printing or projection printing.

(Refer Slide Time: 35:32)



The names are quite revealing, you know. In contact printing, who is in contact with what? The wafer is in contact with the mask. You have the mask, you have the wafer; you put them close together, make them contact and then switch on the UV radiation. So obviously, since the mask is in close contact with the wafer, your resolution is going to be very good, high resolution; exactly what is there on the pattern, there is no gap, therefore exactly that portion will be blocked, rest will be transparent. So, it has very high resolution. Using UV radiation we can go as low as about 1 micron, if you use contact printing technology.

But, what is the demerit? You are putting the mask very close to the, why very close, in contact with the wafer, so the life of the mask is getting reduced; wear and tear, particularly when you have emulsion masks. You know, the emulsion is going to go off, gradually. Also there is this possibility of contamination. If there is some dirt or something on the mask it comes on the wafer; can work both ways. If there is a small dust particle, because this wafer and the mask plate is pressed close together, it can damage the pattern on the mask. So, in general, the life of the mask is going to be low if you use contact printing, but you get very high resolution.

Are you prepared to sacrifice one? Well, if you are prepared to sacrifice a little bit in terms of resolution, then you can go to proximity printing. Proximity - what does proximity mean? Close, closeness, right. That is here the mask and the wafer are placed close together, but not actually in contact. There is a small gap between the two of them which can be of the order of 10 to 25 micrometer. So, you are paying a little bit in terms of resolution, because there is this small gap, so that is why you are paying a little bit in terms of resolution, but the life of the mask is going to dramatically increase. You can have a resolution of 2 to 4 micron. But, suppose you are not happy with this compromise; there are some perfectionists you know, who say that I want the best of everything; want to have my cake and eat it too, I want good resolution and I also want my mask plate to last a very long time. Well, for them also we have a solution and that solution is the projection printing.

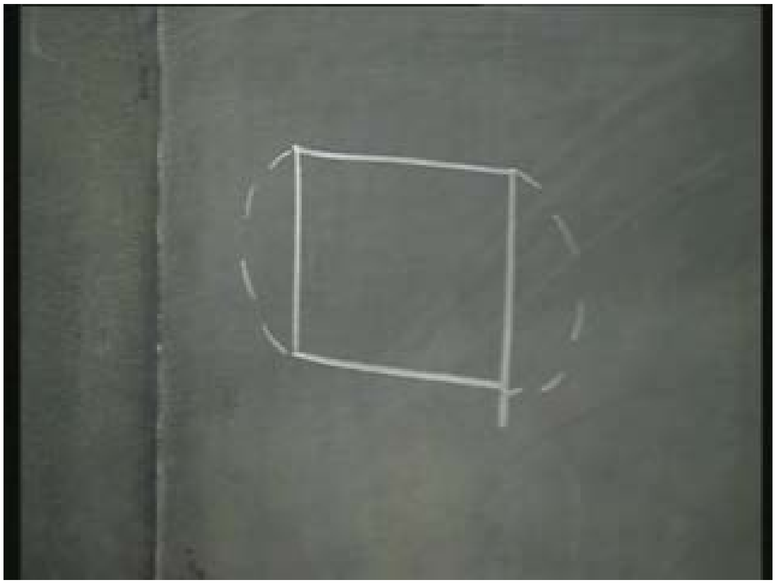
In projection printing, the concept is very interesting. Here the mask is no way near the semiconductor; mask can be here, wafer can be here. There can be a mile separation; in VLSI parlance, this much distance is actually a mile, you know. So, what do we do? We project the image of the mask on to the wafer that is you have some optics involved here. The image of the mask is focused on the wafer. Now, the image can be focused on the wafer, there is no problem of wear and tear, it is not a substantial material, right. But, because I have a highly focused image on the wafer the resolution is also going to be very good. There is no question of any pattern distortion, right. So, you can have really, really you can go down to a resolution of 1 micron, which was the best you could get for contact printing also and there is no problem of any wear and tear on the mask plate; the same mask plate can last you a life time.

What is the price you are paying? Cost; because you need now a complicated optical set up in order to project the image of the mask truthfully, with great accuracy on the wafer. This is the price you are paying. So, essentially therefore we have three types of optical lithography depending on whether the mask is in contact with the wafer, whether the mask is close by but not in contact, in proximity or whether the mask is far away from the wafer and its image is projected on to the wafer. Let us now come, ok, now, I told you that in all these processes, the best resolution in optical lithography we could go to about 1 micron. See, the final limit on optical lithography is set by the diffraction limit, which depends on the wavelength of the light used. Using deep UV light you can somewhat extend the resolution of optical lithography; by using deep UV, you can go to about 0.5 micron, right.

Now, let us come to the question of photoresists. I have already told you that if it gets softened on exposure, it is a positive resist; if it gets hardened on exposure, it is a negative resist. Why or how do these resists get softened or hardened? I will teach the case of a negative photoresist first. You see, a negative photoresist actually has two materials in it, two constituents. One is a polymer; you all know what a polymer is, right? One is a polymer the other is a photosensitive compound. This photosensitive compound that gets activated when it is exposed to radiation; it gets activated, it absorbs energy and it transfers this energy to the polymer molecules, so that, you know a polymer is capable of crosslinking and become, form an even longer chain, right. So, when this polymer molecules gets energy from this activated photosensitive material, they crosslink and when they crosslink, their molecular weight increase and you know, when the molecular weight of the polymer is increasing, they become more difficult to dissolve in any solvent, that is your developer solution.

So you see, the regions which are not exposed to radiation, there the photosensitive element did not absorb any energy, so it could not promote any crosslinking of the polymer chains. These polymers will get washed away when you soak them in the developer solution. On the other hand, the exposed region the photosensitive material will absorb energy, will transfer this energy to the polymer and promote crosslinking and those portions will become insoluble in the developer solution. So, this is precisely what happens. The only problem is this that the unexposed regions will now swell. When you put them in the developer solution, they swell, you know.

(Refer Slide Time: 44:57)



You have a, let us say this was the feature, the unexposed region; it will swell like this. So, what will happen, what is the penalty? Resolution; the feature size on the mask will not be exactly the same as the feature size on the semiconductor. So, in negative photoresist, the resolution will be relatively poor and it will be limited by the swelling of this photoresist. On the other hand, in a positive photoresist also I have two materials – I have one base region (or resin?) and a photosensitive material again. Now, the photosensitive material is insoluble in developer. That is why normally this photoresist will not be dissolved away, if you put it in the developer solution.

But, when this is exposed to the radiation, then this photosensitive material is going to absorb the radiation and become soluble, so that those regions which are exposed to the radiation will become soluble when you put it in the developer solution, whereas the portions which are unexposed, they retain their original property and they are not dissolved in the developer solution. So, this is in essence what a positive photoresist is. The exposed regions become softened, because the photosensitive material is becoming soluble that is allowing it to get dissolved. In the unexposed region, the photosensitive material retains its original property that is it does not get dissolved in the developer solution and the positive photoresist has an advantage that is there is no swelling. Unlike in a negative photoresist where it swelled up, here there is no swelling. So the resolution is better. But, you know it always has a flip side. The resolution is better no doubt, what is the penalty I pay?

The penalty I pay is in terms of throughput. Remember the figures of merit, resolution and then throughput. Why do I pay the penalty in terms of throughput? Because, I must ensure that in the exposed region all of the photosensitive material has had time to absorb enough radiation, so that now it can be completely dissolved. If it has not absorbed enough amount of radiation that is if you have not allowed enough time, then even that will not get dissolved. So, you will not have the proper pattern delineated on this. So, to ensure that the photoresist becomes soft in the exposed region, I must expose it to the radiation usually for a longer period of time than that is necessary in case of a negative photoresist. So, for positive photoresist you pay the penalty in terms of throughput, but you can get better resolution. On the other hand, in case of negative photoresist, you have better throughput, but the resolution is limited by the swelling of the resist.

Just one more point before I forget this thing; in case of negative photoresist, I told you that the photosensitive material on absorption of the radiation, it promotes crosslinking, right; it promotes crosslinking of the polymer. Now, this will hold true only when the ambient does not contain oxygen. If there is oxygen in the ambient, then the crosslinking will be inhibited. The crosslinking will not take place if there is oxygen in the ambient. Therefore, it is usual practice, whenever you have a chance to look at a mask aligner just see that the wafer is always, wafer and the mask, the two together is always placed in nitrogen ambient. That is you have a nitrogen gas supply directed on this wafer mask assembly, so that there is no crosslinking inhibition action of oxygen; particularly important when you are using negative photoresist. So, all the mask aligners have a provision of creating a nitrogen ambient when you are exposing the material.

So, we have discussed the process of optical lithography. In optical lithography I can have three types, three subsections depending on whether the wafer is in contact with the mask or not. I can have two types of resist depending on whether it gets softened or hardened on exposure and I have also told you what the basic chemistry is behind this hardening and softening. However optical lithography has the limitation of resolution. It is 1 micron or at best 0.5 micron if you go to deep UV. Suppose, I want to have a really, really submicron, sub submicron technology, then I may have to employ other means and that brings us to the e-beam lithography, which we will be discussing in the next class.