Fundamentals of Micro and Nanofabrication
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Lecture – 40
Electron beam lithography: Resist process

So, in this lecture we are going to continue electron beam lithography, in particular we are going to look at the resist process. So, so far we discussed about how to profile the beam and what are all the important components in the lithography system and how complex the system is to have dynamic control of the beam. But once the beam is profiled and focused, and then it will be shot onto the wafer that has resist.

So, this resist is sensitive to electrons now. So, optical resists that is photoresist are sensitive to photons, the energy. Then, electron beam resist is sensitive to electron beam. So, the solubility of this resist changes when exposed with the electrons. So, let us look at what is the process and how we do it and also how we increase the throughput of this system by doing some adaptation to the system.

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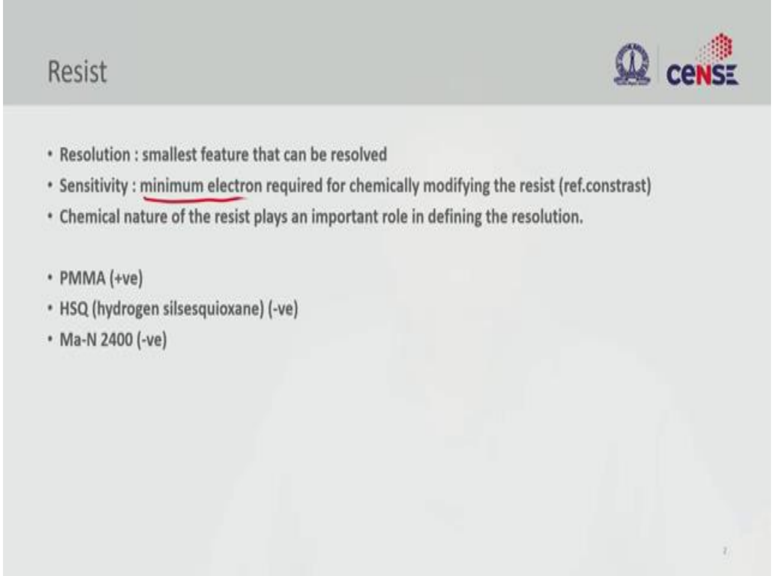

Resist

- Resolution : smallest feature that can be resolved
- Sensitivity : minimum electron required for chemically modifying the resist (ref.constrast)
- Chemical nature of the resist plays an important role in defining the resolution.

- PMMA (+ve)
- HSQ (hydrogen silsesquioxane) (-ve)
- Ma-N 2400 (-ve)

So, there are primary requirements which we already saw earlier in optical as well. So, the resolution meaning here, we need to have a very small feature and the smallest is all we like and the sensitivity of the resist is also very important. So, you want minimum amount of electron in order to create the chemical modification, in this case the solubility change. You do not want to spend too much energy. So, that is the reason why the resist should be sensitive.

So, the chemical nature of the resist also plays an important role because it is not just exposure, but then after exposure you are going to develop the resistance. So, a long chain photoresist will have a lower resolution compared to a short chain resist. So, these are all some typical resist PMMA, HSQ, MaN. So, these are all some standard resist that is used in electron beam writing either positive or negative and their resolutions are also different in nature based on the chemical composition.

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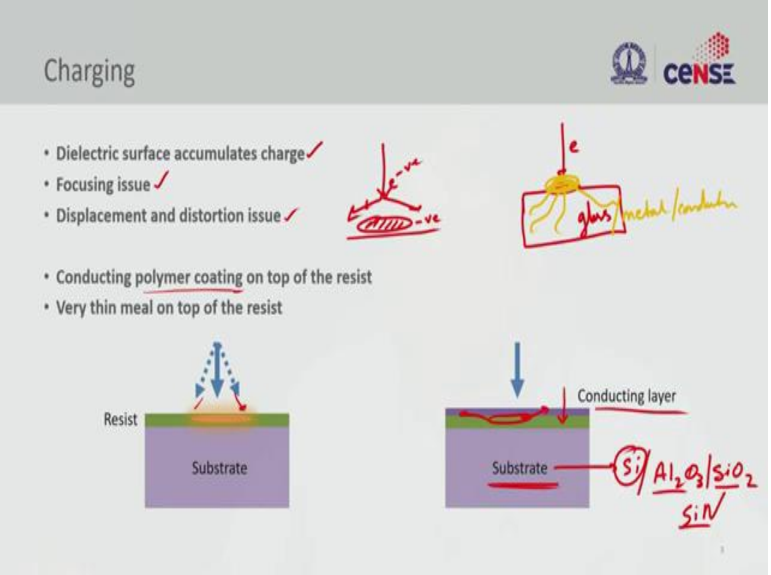

Charging

- Dielectric surface accumulates charge ✓
- Focusing issue ✓
- Displacement and distortion issue ✓

- Conducting polymer coating on top of the resist
- Very thin meal on top of the resist

So, unlike optical lithography we have a special challenge. The challenge is handling charging. Here, what we are doing is we are shooting electrons. So, when you take any dielectric substrate, say glass. So, if I shoot electrons to this glass substrate, what is going to happen is there will be a charge cloud formed here. Why is that?

Because electrons cannot go anywhere because the layer is insulating, but if you take a metal or a conducting substrate, then the electron would dissipate into the material so that you will not have this cloud formed. So, that is exactly the issue here right.

So, if you take a dielectric material, then you start accumulating charge. And what is the problem with that charge accumulation? We have seen this multiple times in very small problems. So, if you have a charge cloud which is negatively charged and then I have electron beam which is also negatively charged. What will happen? This charge cloud here will deflect the beam.

So, this is something we use for a electrostatic lens, but now you are creating this lens on the substrate itself because you are unable to dissipate the charge accumulation here. So, it will create focusing issue. You will not be able to focus it because, of the beam deflection. So, displacement and distortions are the issues that you see because of this charging. So, what can we do? So, that is the cartoon that is captured here, how your beam is getting deflected. So, what to do to address this challenge?

So, put some conducting layer, but that can be easily said, but then we need to think about what do we mean by conducting layer here. So, of course, a conducting layer will take out whatever charge accumulation you have into this, but then this conducting layer should be really thin enough, that it will allow the electrons to pass through without losing the electrons there; without loss of electrons you want to go through. It should be transparent to a large extent that it should not scatter the electrons. So, you want it to be very thin.

So, you can use some sort of conducting polymer or very thin layer of metal. It is very challenging to do it. But an atomic layer of metal or two atomic layers should also do the job, but more often people use conducting polymer. So, PEDOT:PSS is another example of one such conducting layer. There are many polymers one can use. So, if you want to really address this charging issue you can use this, but this strongly depends on the substrate.

If you use a silicon substrate you will not find this problem that much, but then once you go to substrates like a sapphire substrates or say, you have silicon dioxide or silicon nitride as the top layer you will have an issue of charging, while silicon itself may not have this issue.

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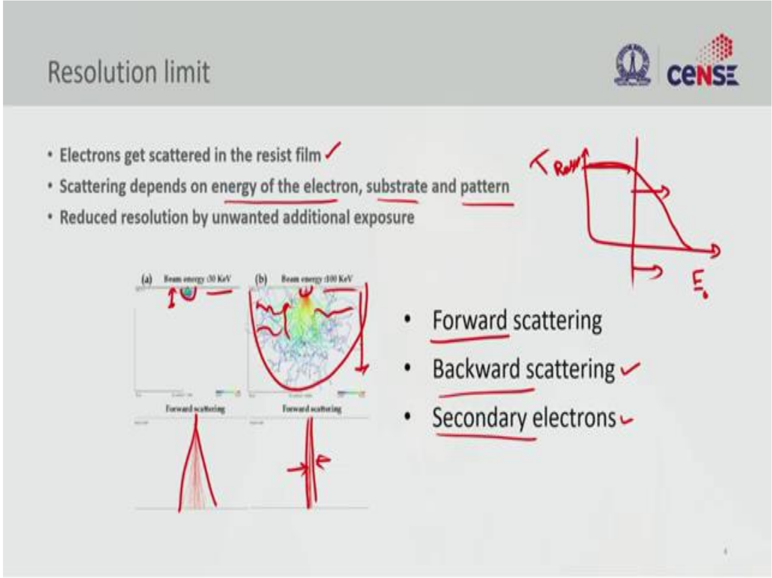

Resolution limit

- Electrons get scattered in the resist film ✓
- Scattering depends on energy of the electron, substrate and pattern
- Reduced resolution by unwanted additional exposure

- Forward scattering
- Backward scattering ✓
- Secondary electrons ✓

So, the resolution is an important question in all lithography. So, what is the resolution limited by? So, when the electron gets into the resist it normally get scattered. And once it achieves a certain energy, then it reacts with the polymer layer and induces chemical change. And this scattering depends on the energy of the electron, the substrate and the pattern itself. So, the scattering strongly depends on all of this and how do we characterize this scattering?

So, this is a simulation of scattering. So, you take a 30 kV beam and then 100 kV beam. So, if you look at it 30 kV beam the penetration depth is very small and it will illuminate this particular region and then you will have a pattern defined here. So, when you increase the energy you can see how deep the electrons are going. So, the electron penetration depth is very small, but when you look at high energy beams; obviously, the beams penetrate deep into the material and now you can see your exposure is very large. So, you must think about whether my feature will come out better with low energy or high energy.

So, in this case lower energies are always better compared to high energy. The real reason for that is not just the forward scattering it is about the backward and secondary scattering as well and that is the reason the bottom image shows you that the forward scattering is pretty sharp here, but then it diverges quickly for a low energy because the energy of the electron here is low. So, it can scatter well, but then if you look at high energy, the forward beam is very sharp. So, from this we should not come to a conclusion that high energy beams are much sharper and then we can define very fine feature.

But the real reason here is the exposure of the electron beam resists not only depend on forward scattering, but it primarily depends on the back scattering and the secondary scattering. So, once you achieve the necessary threshold in the contrast curve which was discussed in earlier lectures. So, you will expose the resist if the beam reaches a certain energy and beyond. So, if you take very a high energy beam, you want to make sure that you only expose this required part. But unfortunately, because of the secondary scattering you will have all the adjacent regions also getting exposed. So, when you are choosing your accelerating voltage, make sure what kind of structure feature sizes you are looking for and what is the resolution that you want. This is not only affecting your resolution, but also proximity as well which we will see later in this lecture.

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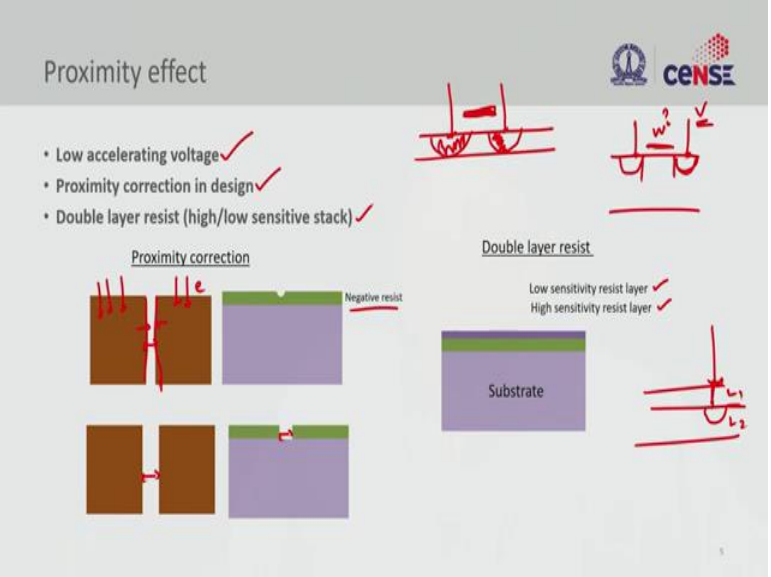

Proximity effect

- Low accelerating voltage ✓
- Proximity correction in design ✓
- Double layer resist (high/low sensitive stack) ✓

Proximity correction

Negative resist

Double layer resist

Low sensitivity resist layer ✓

High sensitivity resist layer ✓

Substrate

So, proximity depends on multiple things. So, accelerating voltage affects proximity. And proximity correction should be taken care in the design itself. It is very hard to control proximity error correction while you are writing. One way of doing that is by using double layer resist that will help you in proximity correction.

So, what is proximity effect in electron beam lithography? So, the bottom left we have the structure has two different width and we use negative resist so; that means, wherever you expose the resist with electron beam, those path stays. And, if your energy is kept identical and then if you increase the width, you will find a broader feature come out better compared to a narrow feature. So, the reason for that is, though you expose it to keep it constant what happens is, you will have some fringe field because of this scattering.

So, just to give you an idea, when I am exposing it will create a exposure volume and and say there is an area next to it, where I do not want to write and then in this case also because of the exposure volume you will write something which is undesirable. But when you use lower energy you will have very less amount of exposure here so, that your blanking part remains the same. So, that is the reason why your proximity effect can be controlled by your accelerating voltage as well.

So, one need to take care of what is the width here and what is the voltage that you are going to do using to handle proximity effect. In more sophisticated cases you can use a bilayer resist; a low sensitive and high sensitive resist, that will reduce the acceleration; Say, I can put layer 1 and layer 2, I can use the high acceleration voltage, but then this layer 1 is going to be very low sensitive material and that will primarily absorb most of the thing and then your second layer is highly sensitive which will be exposed with a lower energy here. So, this is how you can also tackle proximity effect.

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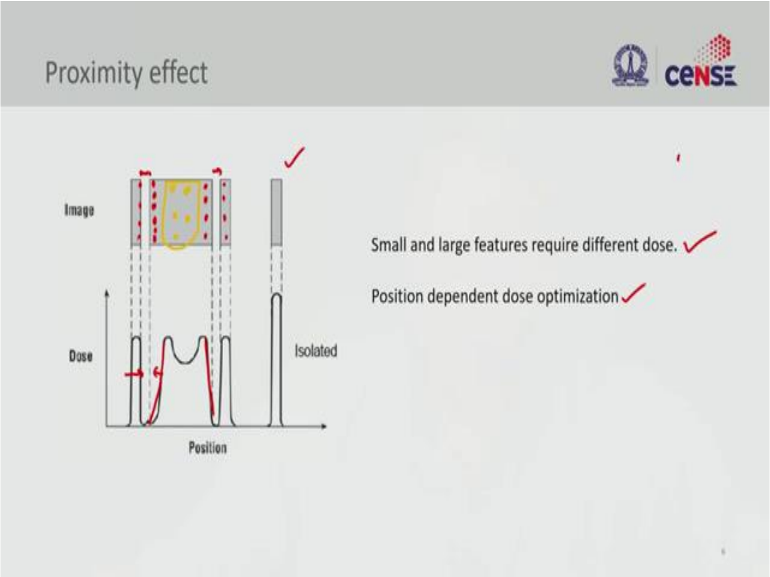

Proximity effect

Small and large features require different dose.

Position dependent dose optimization

And, this is what happens in a real scenario of an isolated feature and a dense feature. So, if you look at the isolated feature it is very nicely defined, but then if you look at denser feature that has some structures on the side you will find that you will not be able to get the right dimension that you want. The reason for that is the dose from these two will affect each other and that will create undesirable critical dimension variation.

So, the best way to do that is to write large features and small features using different dose; in optical lithography you do not have this choice because you do a full illumination. But in this case you are writing so; that means, I can change my energy in required locations. So, whatever I have inside the locations, I can use different energy and then when it comes to the edges I can reduce my energy.

So, this is how you can do large area and small area features to address this proximity effect. So, position dependent dose optimization is what you need to address proximity effect. So, this can be done at the design level itself right before you write it. The design tool will help you in doing this position dependent dose optimization.

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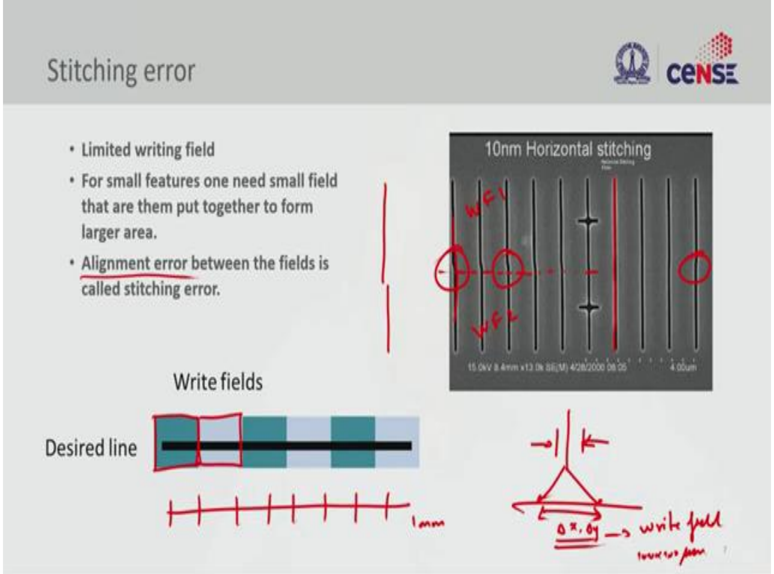

Stitching error

- Limited writing field
- For small features one need small field that are them put together to form larger area.
- Alignment error between the fields is called stitching error.

And the next undesirable thing is the stitching error. What is stitching error? Because we are writing we cannot write the whole wafer in one-go because the deflection region is fixed. So, if the beam is coming and if this is a wafer, I only have a deflection range of you know Δx and Δy in the other direction and this is what it is called as write field; the field within which we can write.

So, this write field can be let us say 100 µm by 100 µm. If my area is 3”-4” wafer then it is impossible to write it with this field. So, what we do is we write it field by field. We move the write field by moving your wafer. But, if our line is 1 mm; so, what I should do is, I should divide this line into write field width and then stitch the line together. So, this is only a problem if your size of these features are larger than the write field that you have.

If the features are within one write field you will not face this stitching error. If your write field is smaller than your feature that you want to write you will find this problem. So, this is all about stitching and you need to have this alignment error correction. So, if you do not do alignment error correction this is what happens. So, that is the SEM picture that you see.

So, this image looks reasonably continuous without noticeable deflection. This is your write field boundary. So, this is a write field 1 and this is write field 2. So, when you are moving from write field 1 to write field 2, you can see a writing error. So, at one point you can see here it is well aligned, but then you can see there is a misalignment between the two write field.

If you want a continuous line, unfortunately if you have write field misalignment you will have this stitching error. In the worst case you will have complete discontinuity. If the lines are completely discontinuous then the structure is useless if you are doing electrical circuits. So, we need to take care of this stitching error.

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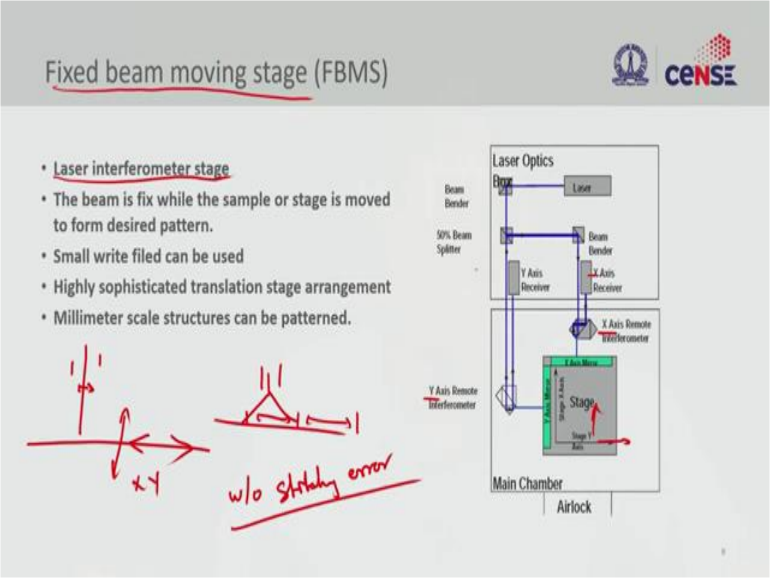

Fixed beam moving stage (FBMS)

- Laser interferometer stage
- The beam is fix while the sample or stage is moved to form desired pattern.
- Small write filed can be used
- Highly sophisticated translation stage arrangement
- Millimeter scale structures can be patterned.

So, in recent systems the stitching error is taken care by fixed beam moving stage. So, instead of keeping the blanker to write this particular write field and then move to the next location, in this fixed beam moving stage, the beam deflection is minimal. So, the beam is not deflected too much. In all practical sense you can assume that the beam is fixed, there is no deflection to the beam, but what we do is we move the stage.

We move the wafer left and right, up and down (there is no change in the height). So, if you do that, then there is no stitching at all because the beam is fixed you are continuously moving and this continuous movement is taken care by laser interferometer stage. It is a high accuracy wafer interferometer stage that takes care of x movement and y movement. By doing this we are we can write millimeter scale structures with very high resolution without any stitching error at all.

So, this allows large area patterning without stitching error that is very important. So, there is no stitching error. So, you can write very large features millimeter sized features, because you are not deflecting the beam since your movement depends on the xy motor. So, there is a xy motor that moves the stage in this. So, you are only limited by that the motor range and not by any of your electron beam deflection and you have sophisticated interferometric setup to control the stage position.

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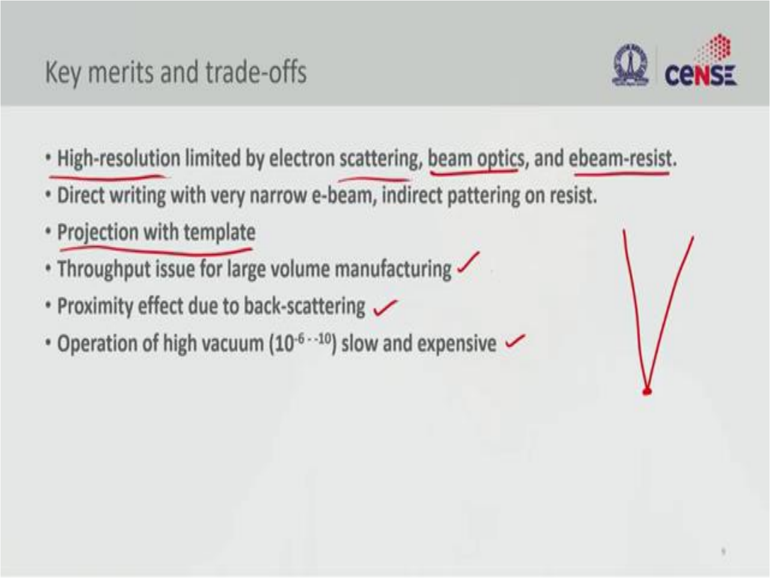

Key merits and trade-offs

- High-resolution limited by electron scattering, beam optics, and ebeam-resist.
- Direct writing with very narrow e-beam, indirect pattering on resist.
- Projection with template
- Throughput issue for large volume manufacturing ✓
- Proximity effect due to back-scattering ✓
- Operation of high vacuum ($10^{-6 - -10}$) slow and expensive ✓

And, overall the key metrics to look for any writing system is the resolution. And, the resolution of any electron beam system is limited by the scattering of the electrons in the resist, the electron resist resolution itself, the chemistry, the beam optics, the lens and so on. So, direct writing of very narrow e-beam can be done, but this is a done on resist. So, if the material is electron beam sensitive, you can pattern it directly if not we do a indirect patterning using resist and you can also do it with the templates which we will see quickly because so, far we just used only pencil beam right which is limited to the spot size we have.

So, you can do projection with templates so, that you can increase the throughput of the system so, that is again very important factor and also control the proximity right. And, one of the downside of all of this is this has to be in vacuum and it is writing. So, it takes longer. So, it is longer and also we have to do it in vacuum which makes the system with slightly higher overhead compared to other systems right.

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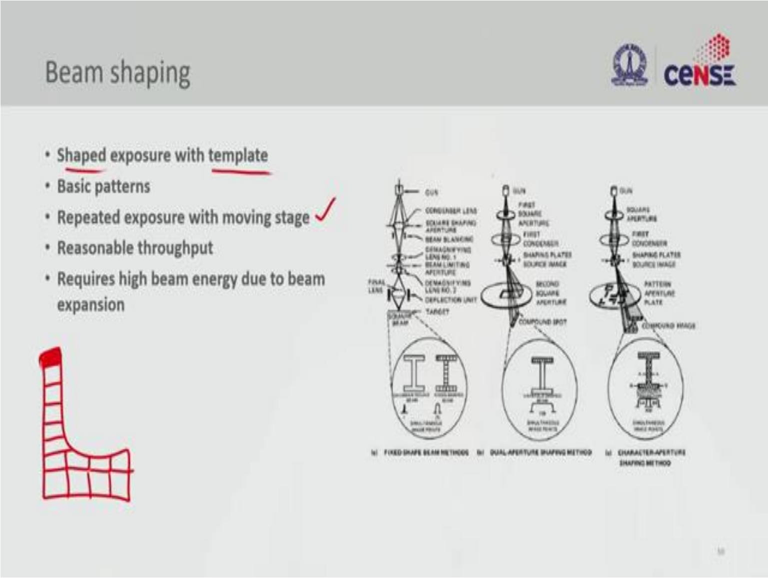

Beam shaping

- Shaped exposure with template
- Basic patterns
- Repeated exposure with moving stage ✓
- Reasonable throughput
- Requires high beam energy due to beam expansion

And this is how we can improve the throughput instead of using a pencil beam. You use a template; there is a shape that we use as a template and then you can repeat that shape along the wafer so, that you can make a pattern. So, for instance if I want to write this pattern very large pattern. So, I will divide this into rectangles. So, I can divide this into rectangles and then I can write these kinds of image.

So, what I need is, this rectangle is written in one go. So, where you know illuminate one area in one go right almost like a projection, but with using primitive shapes and we can do repeat and moving the stage, we should be able to write different patterns. So, this will improve your throughput.

But the downside here is since you must expand the beam, you will end up with the lower energy on the wafer. So, you must increase your beam current that means, you need to increase the energy of your electron gun in order to match this.

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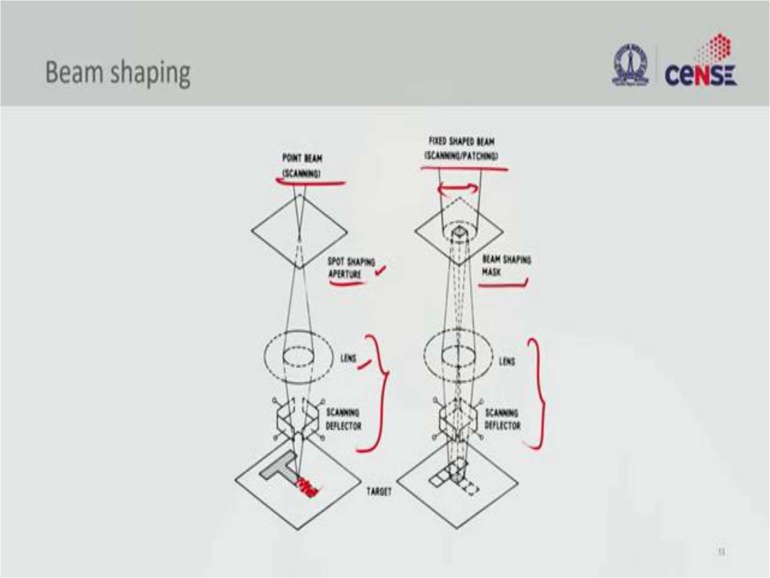

Beam shaping

So, this is how it is done. So, on the left side you see the conventional way of writing where you have the beam shaping where you create the aperture and then you have the lens system and then you do the scanning. But on the right side you what you do is instead of the aperture the spot shaping, what you do is you do a mask. In this case it is just a square right and the square is projected through the system.

You will not see any change in the bottom half that the lens and the deflector remains the same the only thing is, now the beam is already profiled you have a square already and you are just projecting that square. So, since your beam is not a focused beam you are going to expand the beam look and your beam width is pretty large. So, if the beam width is large the current density would also be affected. So, you should also take care of that energy in order to write these kinds of pattern.

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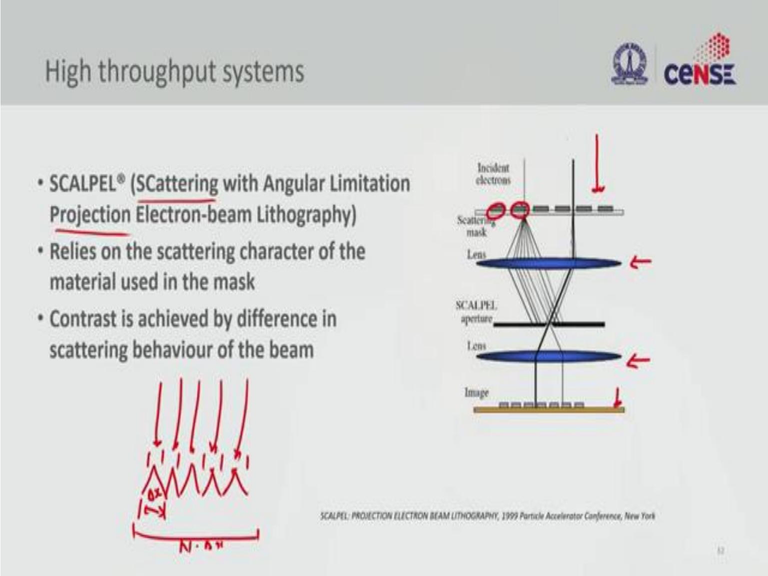

High throughput systems

- SCALPEL® (SCattering with Angular Limitation Projection Electron-beam Lithography)
- Relies on the scattering character of the material used in the mask
- Contrast is achieved by difference in scattering behaviour of the beam

SCALPEL: PROJECTION ELECTRON BEAM LITHOGRAPHY, 1999 Particle Accelerator Conference, New York

And this is you know something that was demonstrated a while ago right to improve again throughput for repetitive patterns. This will not work for arbitrary shapes; it will only work for repetitive pattern that uses a scattering from the repetitive pattern you have which is called scattering with angular limitation projection electron beam lithography. So, we are looking at projection like system for electron beam lithography, that uses scattering.

So, here you have the beam coming from your source; a profile beam and then you have the scattering objects. And, these scattering objects is going to scatter the electron beam by using again the lens system. These lenses are electro-static magnetic lenses, that will capture the electrons and then project it onto the image. So, this remained mostly a demonstrator, but this is one of the possibilities to do it, but recently people have come up with multi-beam writing.

That is the most interesting part where instead of using a single beam, you will use multiple beams and these multiple beams will have individual deflectors and this individual deflectors can write a multiple area. So, what you are trying to address is, you are going to increase your write field. So, initially with a single beam this was your write field Δx let us say, but now ‘n’ number of beams will increase my write field with the same quantity. So, there are thousands of beams that one can use in order to do that and that is called multi-beam writing, which is explored very seriously as an alternate writing process for next generation CMOS.

So, this is still in R&D phase and there is a start up there is working on this, we will see how that evolves, but this is another interesting configuration that has evolved over the year. So, with that we come to end of this lecture, where we elaborated on the resist process and how the energy is affecting your resolution through proximity and so on and how to correct those. And, also we saw alternate form of illumination by using shaped beams to improve your throughput and also you can use multi beam which is an evolving technology.