Biophotonics
Professor Basudev Lahiri
Department of Electronics & Electrical Communication Engineering,
Indian Institute of Technology Kharagpur
Lecture 53
Nano-Lithography: The Art of Small

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Hello. So, I have one more prop for you today. I hope you are not disliking these props too much. Previously I brought I think fluorescent marker, then tweezer, and today again I have stolen this from my daughter. Well, she gave me permission at the end. First, she was crying, because she, this is her toy that she plays with. This is basically a stencil. She draws circle through it.

So, she paints on top of this and there is a page like this beneath and the paints gets blocked by the solid part of the stencil and the paints go inside this and thereby four circles as such this particular design forms. So, this is what stencil is or stencil art is. I am pretty sure all of you have used it, have seen it. This is pretty common.

We utilized something very, very similar to this in nanofabrication. Today, I am going to tell you all about that. So, welcome to the topic of biophotonics and today we are discussing Nanolithography: The very Art of Small.

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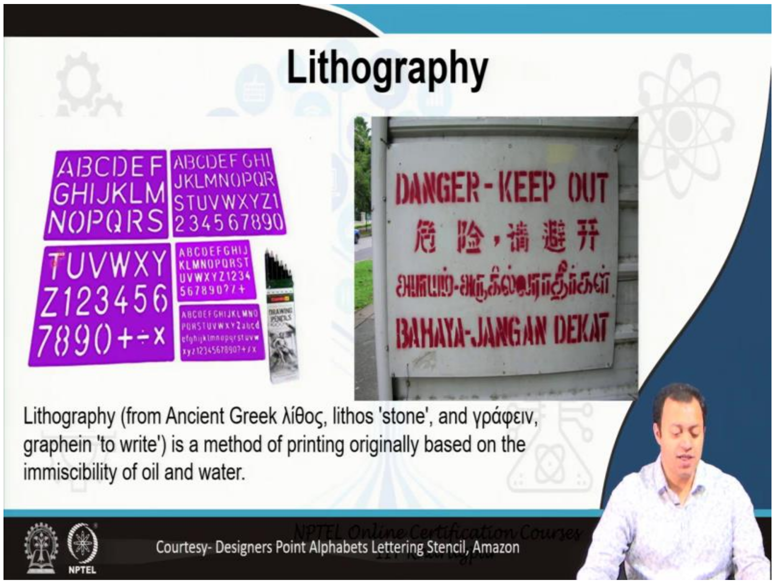

So, this is your stencil. I even got it these images from Amazon as such. This is the stencil. You spray paint over it. Selectively the paint passes through these holes, these stretches, and you get some amount of letter coming out. Rest of the place the paint is blocked and it remains as it is. So, this is what a stencil can do. You can utilize stencils to make printing, make some kind of a message, make some kind of an image, make some kind of a picture.

And though, this is not technically directly lithography, because lithography was usually based on immiscibility of oil and water fact basically. They were using lithographic techniques in Germany during I think 16th or 17th century to cheaply print pamphlets for their plays. But you get the idea, some kind of cheap and easy printing method.

You simply need to spray some amount of paint over it, some of the paint will pass through the trenches, pass through the hole, some of the paint will not pass through. Previously they made this difference between some paints are soluble in water, some paints are not. Remember, as a child you must have played invisible ink. You have made use of invisible ink, some kind of lime juice or lemon juice in which we put something.

We write something on a piece of paper. Let it dry. The paper remains blank. But when we put this paper in front of some sort of a lamp or something, we used to do it in front of a lantern which generates heat. The heat will coagulate or heat will react with lime juice and you see some kind of image or some kind of message forming out, so somewhat of a similar thing.

You write something. You selectively write some kind of an image, some kind of a message through these stencils. All of us know this. All of us have used it or have seen these kinds of signboards where this kind of printing has been done. In nanofabrication, we do the same thing. We do the exact same thing. Instead our masks or these stencils, we call them mask, are containing images, geometric patterns that represent circuit. They are slightly smaller. And instead of sending paints, we send light.

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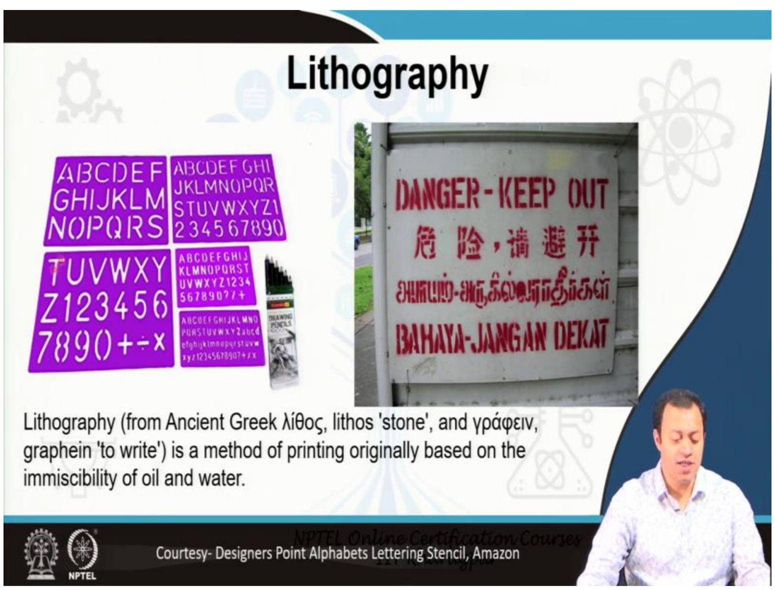

This is a photomask. This is quite big. But as you can see, each of these areas contains numerous amounts of geometric patterns. And all of these patterns represent certain area, certain circuitry that needs to be utilized in making a total integrated circuit IC or as colloquially call as chip, an electronic chip, a silicon chip, a chip.

So, this is a photomask, a stencil, whose particular image or whose particular pattern we need to project into our screen, whose particular pattern, whose particular image we need to project on our screen. This part is your screen and you want to make this sort of message, this sort of an image, this sort of a letter here. So, now, imagine the same thing instead of red paint, you have light, and instead of this white board, you have a piece of silicon and that is what your photomask does.

If there is a pattern per se, that pattern, the geometric pattern like previously the letter pattern represented, this pattern represented a letter, a message, you could draw some amount of image out of it. Here, we are having particular sets of circuitries being imprinted upon a piece of silicon chip. And that is overall the process of optical lithography or photolithography as this say.

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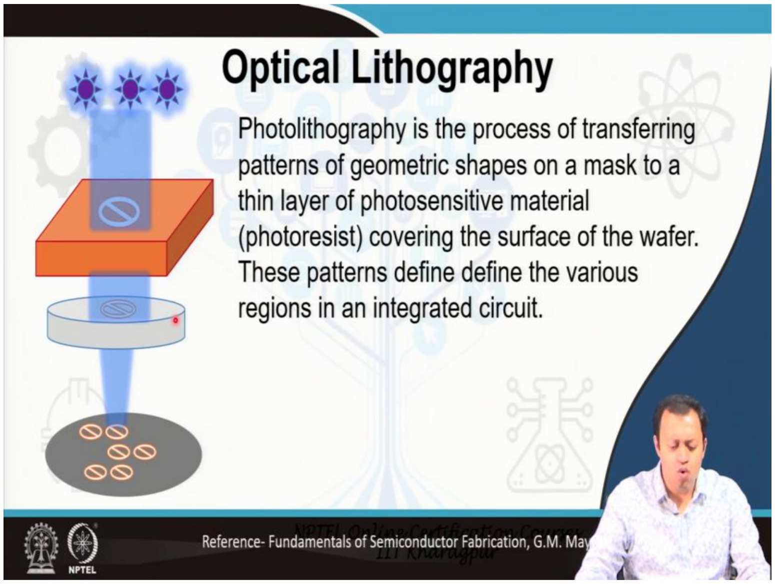

What is the procedure? Photolithography is the process of transferring patterns of geometric shapes on a mask, mask is the stencil here, to a thin layer of photosensitive material, a photoresist, that covers the surface of the water. These patterns define, I put define twice, the various regions in an integrated circuit. So, what is the overall procedure? I have a cool animation for you, which I made myself.

So, you start with some kind of a UV light source, an ultraviolet light source roughly around 350 to 300 nanometer wavelength that you pass through some kind of a stencil. This is your stencil with this part is open. We usually covered this with some kind of gold or chromium alloy. Gold and chromium alloy usually reflect these types of UV radiation of this specific frequency, not all. And some amount actually manages to pass through this stencil as this open area, just like paint can pass through it, just like paint can pass through the middle of this, but paint cannot pass through the solid part.

The light, the UV light can simply pass through it. Once the UV light passed through it, we put some sort of a lens, some sort of a confocal lens, some sort of a converging lens that lens converges or focuses this UV light into a very, very small, tightly bound, tightly focused area around roughly feature size that optical lithography can go on an average is 1 micrometer. Though people claim they have gone way beyond that, 1 micrometer is the roughly feature size.

And you put a photosensitive material that has covered your silicon chip and that will get projected, that will get imprinted. So, overall, this happens to be your screen, this is your paint and this is your stencil. So, painting or more precisely printing or more precisely writing with light, you simply move this wafer which is covered with a photoresist, a photosensitive polymer in x and y direction using a piezo stage very, very precisely, nanometer by nanometer, 1 nanometer at par second, 1 nanometer in x direction per second, 1 nanometer in y direction per second. It is a bit more than 1 nanometer, but you get the point.

If we move this stage, like you move the microscope stage very precisely, very correctly, very slowly, very nicely, very smoothly, you can have this very big image printed because of the convergence of the light field by the lens, this is overall the lens, on to a small area and that can be repeated. Now, I have put a very, very simple geometric pattern, but as you saw in the previous slide, the geometric patterns or the geometric shapes are pretty much complicated, are very, very complicated each part representing some sort of an integrated circuit part.

It can be your transistor. It can represent a resistor. It can represent a capacitor. It can represent a diode. It can represent interconnects. Overall, all the representation, all the messages, all the patterns that you need to draw, you need to make on top of a chip is put here. So, thereby the photomasks are complicated, but once done, you can utilize it several times.

Once done, once you have made it, once you have made a master copy, consider it like a template. You have a template and you are printing it 10,000 times on different leaflets and that is coming out, that is giving you the same message over and over and this is the same thing. This is the say template photoresist, a mask, a photomask, a template of making a specific processor, Intel Pentium 5 or something like that.

Much more complicated structures, but the overall idea, the overall technique remains just like this. You simply shine light through it. The light needs to be converged, light needs to be focused. This could be big. This size could be big. It could be few millimeters, does not matter. It is then converged using this lens. This is actually a lens, not a disc. This is a lens. I could not draw a proper lens, but you get the point.

This is a, this could be a proper lens, like a concave lens and that focuses in a very, very tight spot and that imprints the pattern on to photosensitive material, which you have coated on top of your silicon wafer. I am saying silicon, it could be substrate, it could be glass, it could be gallium arsenide, it could be anything. So, now what exactly is this photoresist thing, what exactly is this photosensitive material?

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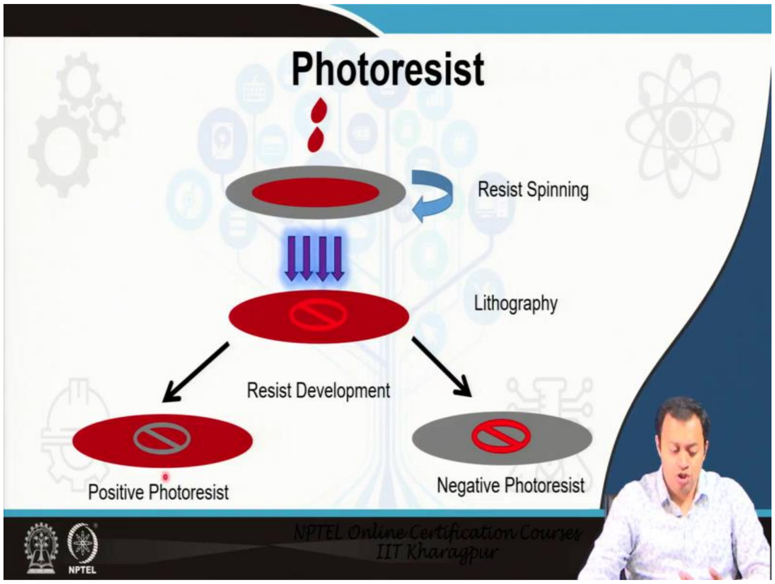

So, what you do, you first take this photoresist which is a polymer usually a liquefied form and then you drop it like a dropper on a flat disc like wafer and then spin it at a particular RPM. By spinning at RPM very, very thin layer can form. Some amount gets radially propagated. And it is basically spin coating. I am giving you the easiest and the simplest method.

You cover the entire thing with some sort of a polymer by spinning it at a particular RPM, so that more or less a uniform thickness is made and then you can bake it for adhesion purposes. But overall spinning uniformly at a specific speed gives a proper thickness of this polymer on top of your wafer, which you then subject to optical lithography, photolithography that is with a stencil in between, with the photomask in between so that this particular pattern is imprinted.

And then depending on your resist, whether it is positive or negative, you develop it, which means what. So, this photoresist is a photosensitive material. It is a polymer which is photosensitive. So, those areas where light falls on to it, it undergoes some kind of a photochemical reaction, some kind of a modification in its polymerization state.

Either the photon that is falling, that is reacting with the molecular chain this photoresist has made, either it simply weekends or breaks, it breaks or weakens the polymeric chain, where the light is falling, the photon is breaking the polymeric chain, weakening it or sometimes there is a cross-linking of the molecule because of the generation of extra electron a cross-linking of molecular chain. So that is how we define positive photoresist or negative photoresist.

In positive photoresist the area where light has fallen, the molecular chain breaks or molecular chain weakens. In negative photoresist, where light has fallen, the molecular chains strengthen up, they cross-linked. This is simply the difference. At one part, depending on the polymer, depending on a specific polymer, it weakens.

At another part, the opposite photochemical reaction takes place in which the photons generate cross-linking of the molecules. So, after this lithography process has done the area which was exposed have a different chemistry, different molecular properties, slightly different molecular property than its neighboring side, then its side where it has, where light has not fallen or where light has been blocked.

Either this thing has weakened itself, the molecules have weakened itself or this is the area where the molecules have cross-linked themselves, strengthened themselves. You then put it into some kind of a developer. A developer is a very, very selective solvent, usually methyl isobutyl ketone or something similar. The resist, there are several different types of resists SU-8, these are highly classified, their exact formula, how strong they will react, etc., etc., but you get the point.

The developer is a solvent that selectively eats away the weaker portion depending on certain condition how long you have put it in the developer solvent 1 minute, 2 minute, 10 minutes, 100 minutes, how strong the developer solvent is, what is the temperature of reaction. But overall, they, it has been optimized. So, the developer solution eats away dissolves the weakened part.

In this particular case, the positive photoresist, the exposed area is the weakened part, which has been dissolved, thereby leaving the bare silicon part, making a pattern. In a negative photoresist, the weaker part is the area which was not exposed, because this area has been cross-linked. So, they have been, the weakened part has been removed. Now remember, the developer is different for this one, the developer is different from this one.

It is not the same solvent that, it can be used, but usually not. The same solvent is not used for developing both positive and negative photoresist. Now, I am hesitant to give you like never or absolute values or absolute numbers because nanofabrication just like his cooking. There is no one fixed method of cooking. You put oil and then salt and then sugar and then your vegetables. Some person does the exact opposite.

They first dry heat and then put salt at the very end. So, there is no specific formula. There is no specific method. This is as much art as much as science. But usually this is a milder developer or milder reaction take place. Otherwise, this might eat up everything. So, you only eat away this weakened part. Whereas in this case, the strengthened part is remained as it is.

The original resist has been weakened. And obviously there are different types of resist. I am doing a schematic for simplistic purpose just because the developer is also different, the resistor is also different and they look different. They have different texture. They have different molecular weight. And then they are different, obviously, photosensitive property.

So, overall, this is the process by which you can make a pattern, some kind of pattern type thing onto the polymer which is coated on top of a silicon resist, silicon wafer or a substrate or any kind of a material which you need to pattern at a nano level. And these scales, because I said a lens is used and UV light is used, you can very much make them length, breadth and, length and breadth x and y, few micrometer scales. How much was the width of your hair again? Remember that. So, anyways, so now you see depending on the positive photoresist or negative photoresist you have certain areas of the wafer exposed.

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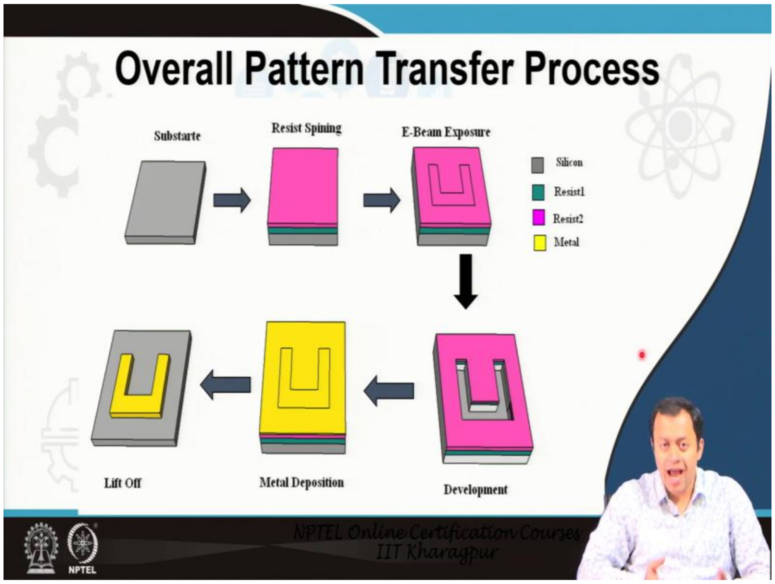

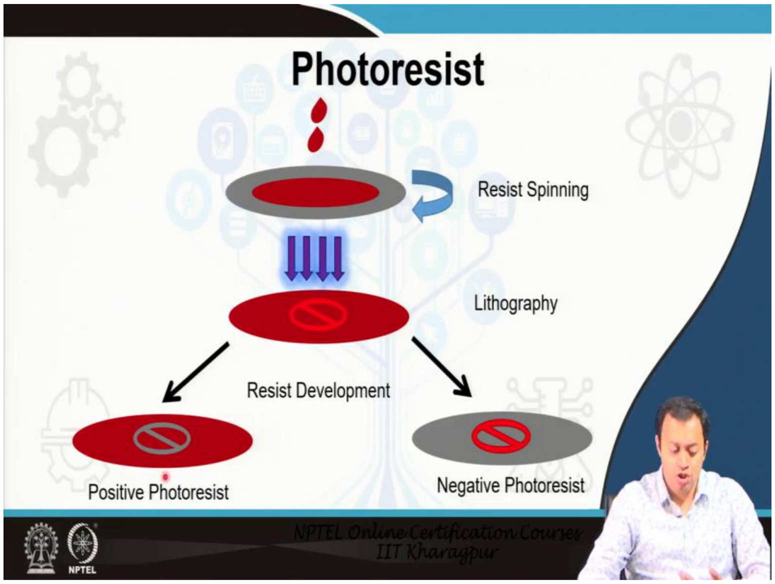

Then the exposed area needs to undergo some sort of either subtraction or addition. Either you subtract some material out of it or you add some material to it. Remember, previous class addition or subtraction. And thereby, overall pattern is generated. This is my way. This was my recipe. This is my image of making split ring resonator.

You remember split ring resonator from metamaterials. So, I took a substrate. I coated resist. These are the resists. These are the photosensitive resists. I exposed it to electron beam actually, but consider it as optical light, UV light. And UV light pass through a stencil. This was the area that was exposed. This was the area that was the rest was not exposed. This was a positive photoresist.

So, the positive photoresist was removed. The positive photoresist was developed and removed. That area the whole I then subject it to some sort of an acid. The acid ate my substrate. The polymer was not touched by acid. Usually polymers are or this specific polymer was nonreactive to the acid. So, we, I make a trench, a hole, then I covered the entire surface with gold. Gold was here and gold was there. There was a height difference.

So, if this depth was like 1 micrometer depth. I put 100 nanometers of gold. So, some gold was put here, some gold was put there. The gold which was in the trench, the gold which was in the hole was not connected with the gold, which was on top, because there was small amount. And then I put it in some sort of a very strong solvent, which dissolve the entire resist completely acetone, basically, something that dissolves your nail polish, nail polish remover, a strong nail polish remover. The acetone dissolved everything.

So, the gold that was connected with the polymer got washed away. The gold that was not connected with the polymer remain as it is. And remember, the gold on top and the gold on bottom were different. So, it is like this. Again, I put gold or paint through it, some part remains here and some part where at the bottom. You remove this and you have a pattern here. We have a pattern here.

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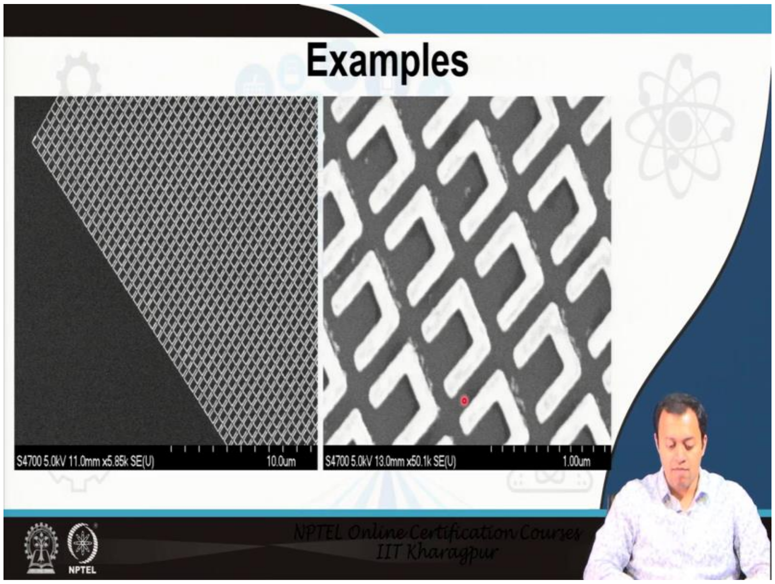

And I have beautiful images to share with you. These are my metamaterials. You have the scale bar here, you have the scale bar here and you can measure. So, remember these are the U-shaped metamaterials. These are gold fabricated on top of silicon. So, this part is the inductor. This gap is the capacitor. And when I shine light with electric field across the gap, there is a circulating electric current that opposes, that produces a perpendicular or orthogonal magnetic field. That magnetic field is anti-parallel and you have your metamaterial effect.

You have this kind of structure. So, these are all, all made by me as you can see beautifully how I have arranged. It was just passing through a stencil, which has one U shaped and then I simply moved the stage first here, then here, then here just like you do in printer. Previous old time you used to have a printer where the inkjet goes like this. Dropping ink at one place, not dropping ink at one, another place and thereby you have a and b. You now understand what, how this is made, how a metamaterial is made, which I have used for biosensing purposes.

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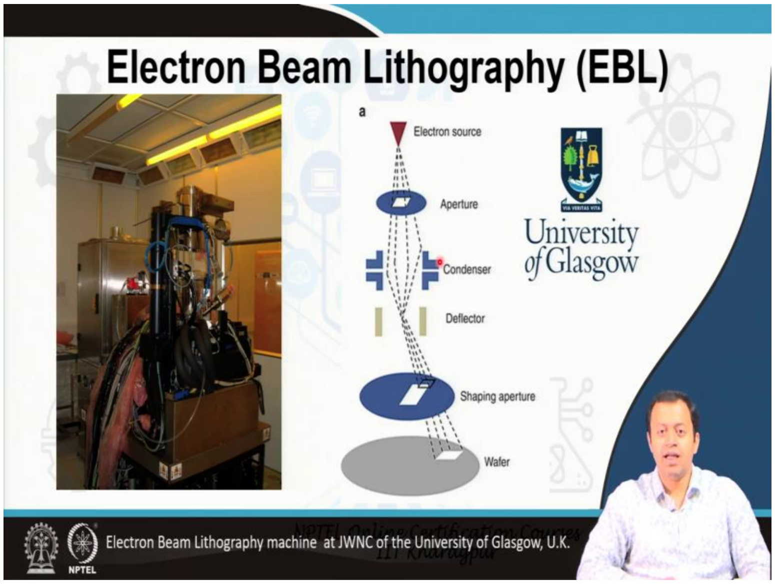

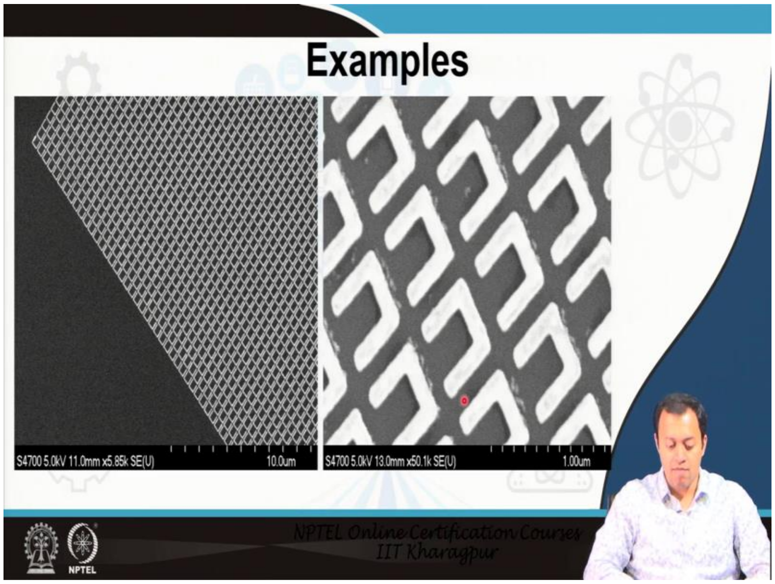

So, obviously, when we have stencil-based things for optical lithography, photolithography that is, we also have electron beam lithography, where instead of sending light you send electrons. So, this is basically your cathode ray oscilloscope type thing. I keep on sharing, keep on telling you about that. It is just that your optical, your electron beam lithography, you can control your electron by magnetic plates and electric field and electrons usually can be focused at a smaller area than the light can be focused.

Light usually suffer from diffraction limit, remember. Electrons also can suffer from diffraction limit, but using magnetic plate and focusing areas, you can, a condenser aperture, you can actually focus streams of electrons on to a particular area. That electron needs to be put into a wafer, which contains electron beam resist. Resists which are sensitive to electrons falling onto them.

Again, the same thing happens, instead of photons, now electrons fall on to these polymers and they either break their molecular chain breaks or they have a cross-linking, but overall same positive resist, negative resist, previous was positive, photosensitive, now it was positive electron sensitive, previous was negative photosensitive, this one is negative electron sensitive and this is the VB6 machine that I used during my study at my alma mater in University of Glasgow.

Do you know what alma mater actually means? It means nourishing mother. So, this is the nourishing mother that nourished me, nurtured me, made me face the world. What I am today is because, just because of this institution. And this I was fortunate enough to utilize this machine. In fact, all those images that you saw were not exactly optical lithography, but electron beam lithography. But overall the concepts remain very, very close. The concepts of writing or printing is very, very close.

Sometimes also in electron beam lithography, you do not need to put a stencil, you can have a CAD-based tool makes the electron beam gun or makes the stage move in a particular x, y direction and thereby you can have the, like a printer, like the printing technology, like your computer printer has changed or progressed rapidly this is also something very, very similar. Overall, concept remains quite close to one another. If you know one, you will not have problem to you know jump to another one. So, this over all is the writing process, the printing process.

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This is how we write geometrical patterns on to a substrate and that substrate, that geometrical pattern, different areas of that geometrical patterns represent different circuits, the geometrical patterns, either they themselves or different areas by themselves represent different areas or different parts of integrated circuit.

One type of geometrical pattern represent diode, one type of geometrical pattern can represent or can be made into a capacitor, inductor all those electronic circuit elements. And combining several of them lumped together you make an IC and that is it. That is basically something that I taught you today.

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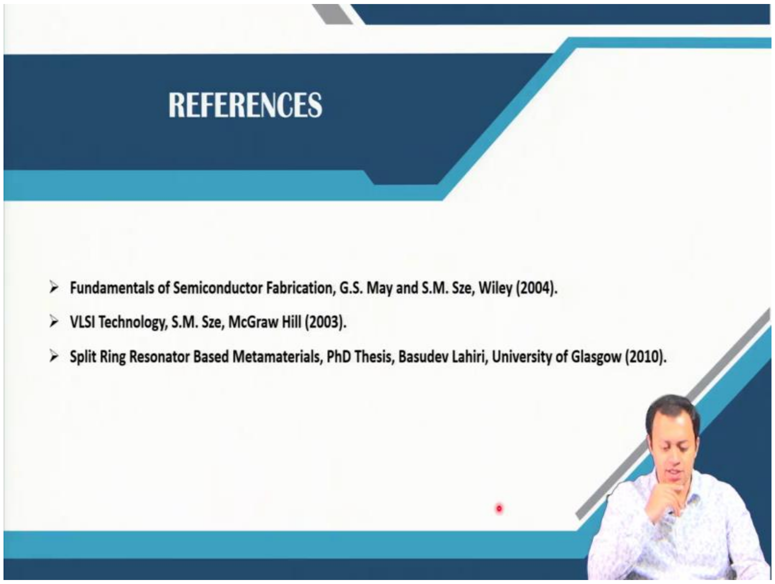

And these are some of my references. If you want to go through it, please go through it. The S.M. Sze is basically the godfather of any nanofabricator. No nanofabricator to the best of my knowledge can progress without referring to some of the phenomenal work that this gentleman, this Taiwanese gentleman S.M. Sze has done.

And it is it is a dream of every nanotechnologist, every nanofabricator to once or twice go and see meet S.M. Sze who to the best of my knowledge is still alive lives in Taipei, but I could be, I could also be wrong. So, I will continue with the course in the next class. Thank you very much.