Course Name- Nanophotonics, Plasmonics and Metamaterials

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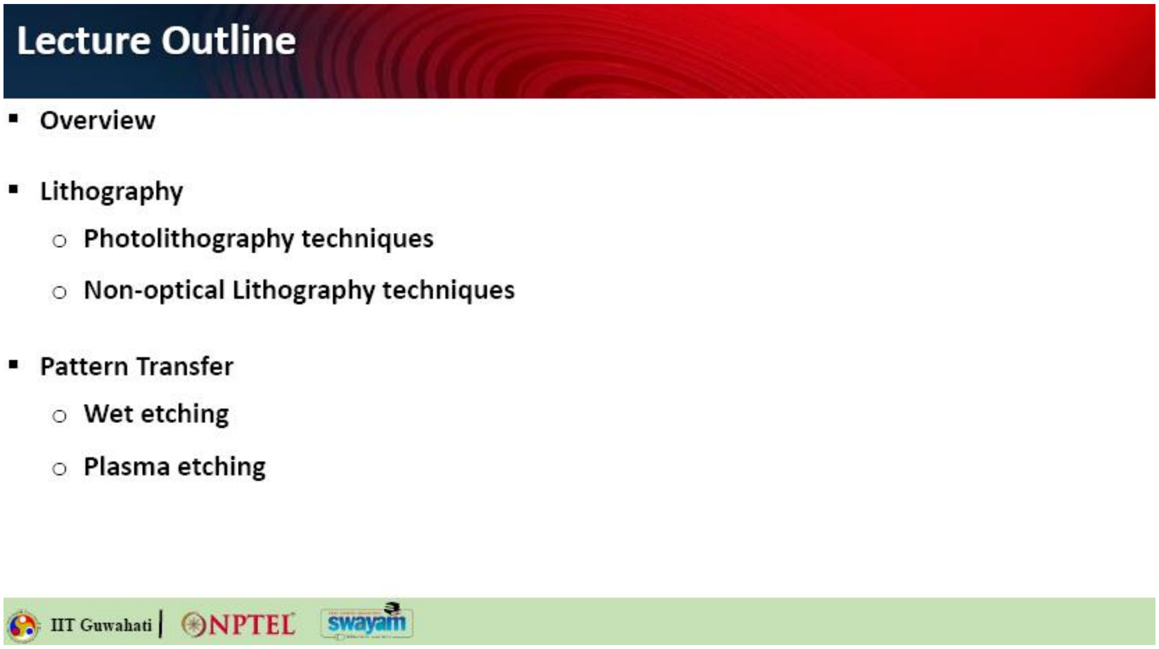
Week-12

Lecture -35

Hello students, welcome to lecture 35 of this online course on Nanophotonics, Plasmonics and Metamaterials. Today's lecture will be on lithography and pattern transfer. So here is the lecture outline. We will first look into the overview of this topic. Then we discuss about different lithographic techniques. As you can see we will discuss about photolithographic techniques and non-optical lithographic techniques.



Lecture Outline

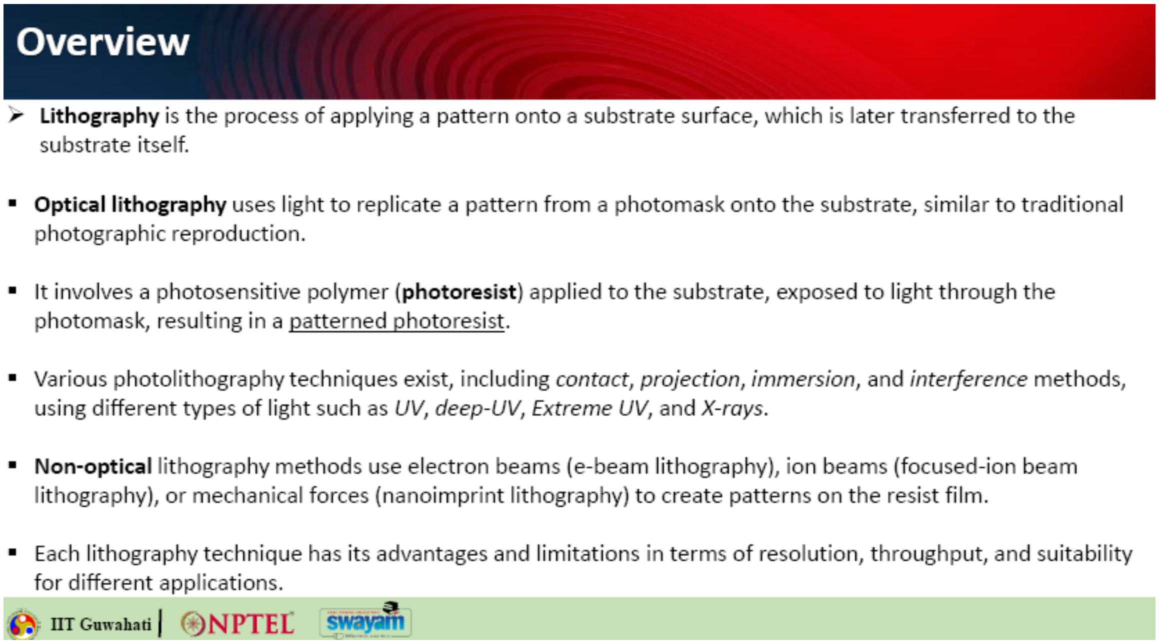
- Overview
- Lithography
    - Photolithography techniques
    - Non-optical Lithography techniques
- Pattern Transfer
    - Wet etching
    - Plasma etching

So this photolithography can also be called optical lithography techniques. And then we will look into the pattern transfer methods like wet etching and plasma etching. So overall this particular topic will be briefly covered in this lecture. Now in the previous lecture you have seen that we have covered different methods of depositing thin films.

Now we will look into the methods or techniques related to lithography where we are able to make some patterns on those films or in the substrate itself. So lithography is the process of applying a pattern onto a substrate surface which is later transferred to the substrate itself. So optical lithography or photolithography as the name suggests it uses light to replicate a pattern and the pattern is actually made in the photo mask and from the photo mask you are basically transferring that pattern onto the substrate. So this is typically very similar to the traditional photographic reproduction. So you can think of those methods and you will find an analogy here.

It involves a photosensitive polymer which is also called photoresist that is applied to the substrate. Then it is exposed to light and it is exposed to light via the photo mask. So only those portions which are to be printed that particular pattern is formed in a way on the photoresist. So that actually gives you a patterned photoresist. So, we will go into more details of the photoresist in this lecture only and we will tell you about positive and negative photoresists.

There are different types of photolithography exist which are called contact, projection, immersion, interference methods and they also use different types of lights as you can see UV, deep UV, extreme UV, X-rays and all these things. So there are applications for each of these. So what varies here is basically the wavelength so you can understand the feature size that you are trying to develop will also shrink as you go from UV towards X-rays. Besides optical lithography there are also non-optical lithography methods which use electron beams. So, this kind of lithography is called electron beam lithography.



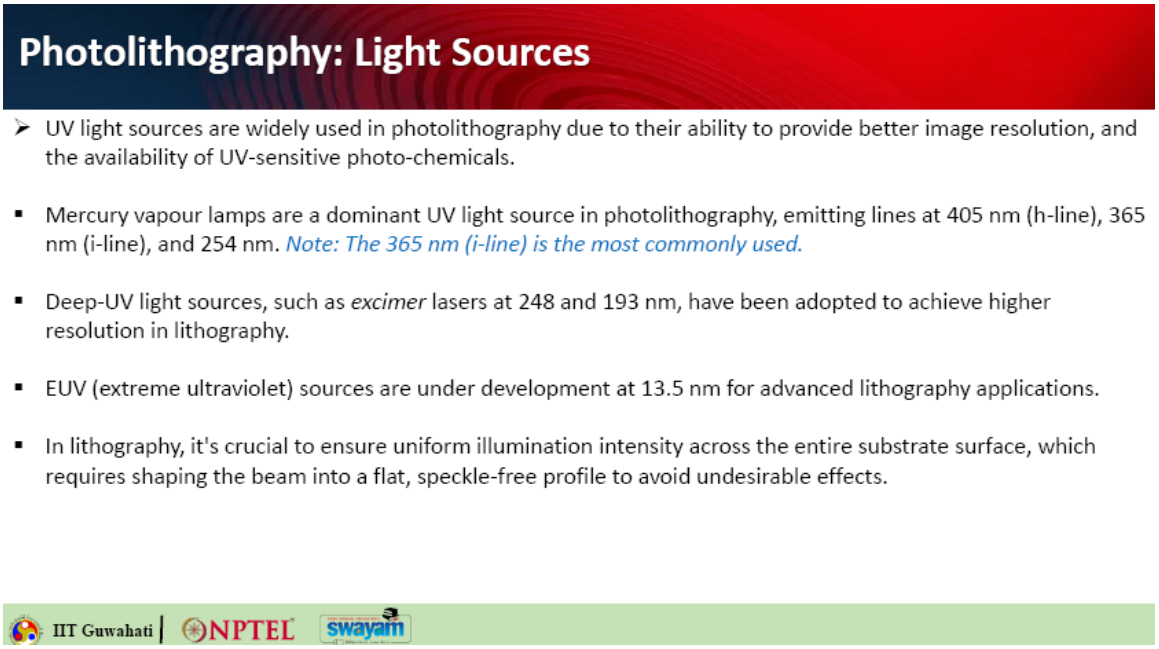
Overview

- **Lithography** is the process of applying a pattern onto a substrate surface, which is later transferred to the substrate itself.
  - **Optical lithography** uses light to replicate a pattern from a photomask onto the substrate, similar to traditional photographic reproduction.
  - It involves a photosensitive polymer (**photoresist**) applied to the substrate, exposed to light through the photomask, resulting in a patterned photoresist.
  - Various photolithography techniques exist, including *contact*, *projection*, *immersion*, and *interference* methods, using different types of light such as *UV*, *deep-UV*, *Extreme UV*, and *X-rays*.
  - **Non-optical** lithography methods use electron beams (e-beam lithography), ion beams (focused-ion beam lithography), or mechanical forces (nanoimprint lithography) to create patterns on the resist film.
  - Each lithography technique has its advantages and limitations in terms of resolution, throughput, and suitability for different applications.

There are lithography that uses ion beams which are also called focused ion beam lithography. There are methods like you know where mechanical forces are applied to create pattern on the resist film. This kind of method is called nano imprint lithography. So we will briefly look into all these different topics in this particular lecture. Now you have to keep in mind that each lithography technique has its advantage and disadvantage in terms of the resolution, throughput, suitability for different applications.

That is why all these different methods have been practiced depending on your need and the application demand. So when we look into photolithography first it tells you that photolithography means light is involved. So you can think of the light sources and popularly UV light sources are widely used in photolithography and that is because of their ability to provide better image resolution and the availability of UV sensitive photochemicals. So these are the main two reasons. UV as you can understand these are high energy as compared to the visible so they have shorter wavelength.

So mercury vapour lamp are dominant UV light source in photolithography and they are able to emit lines at 405 nanometer which is called H line, 365 nanometer that is I line and 254 nanometer. Now remember that among these 365 nanometer or the I line is the most commonly used one. Now deep UV light sources such as excimer lasers which are operating at 248 and 193 nanometer they are also adapted to achieve higher resolution. So shorter the wavelength deeper you move into the UV you are able to achieve higher resolution. Now if you look into excimer lasers these are basically short form for excimer dimer laser.



Photolithography: Light Sources

- UV light sources are widely used in photolithography due to their ability to provide better image resolution, and the availability of UV-sensitive photo-chemicals.
- Mercury vapour lamps are a dominant UV light source in photolithography, emitting lines at 405 nm (h-line), 365 nm (i-line), and 254 nm. *Note: The 365 nm (i-line) is the most commonly used.*
- Deep-UV light sources, such as *excimer* lasers at 248 and 193 nm, have been adopted to achieve higher resolution in lithography.
- EUV (extreme ultraviolet) sources are under development at 13.5 nm for advanced lithography applications.
- In lithography, it's crucial to ensure uniform illumination intensity across the entire substrate surface, which requires shaping the beam into a flat, speckle-free profile to avoid undesirable effects.

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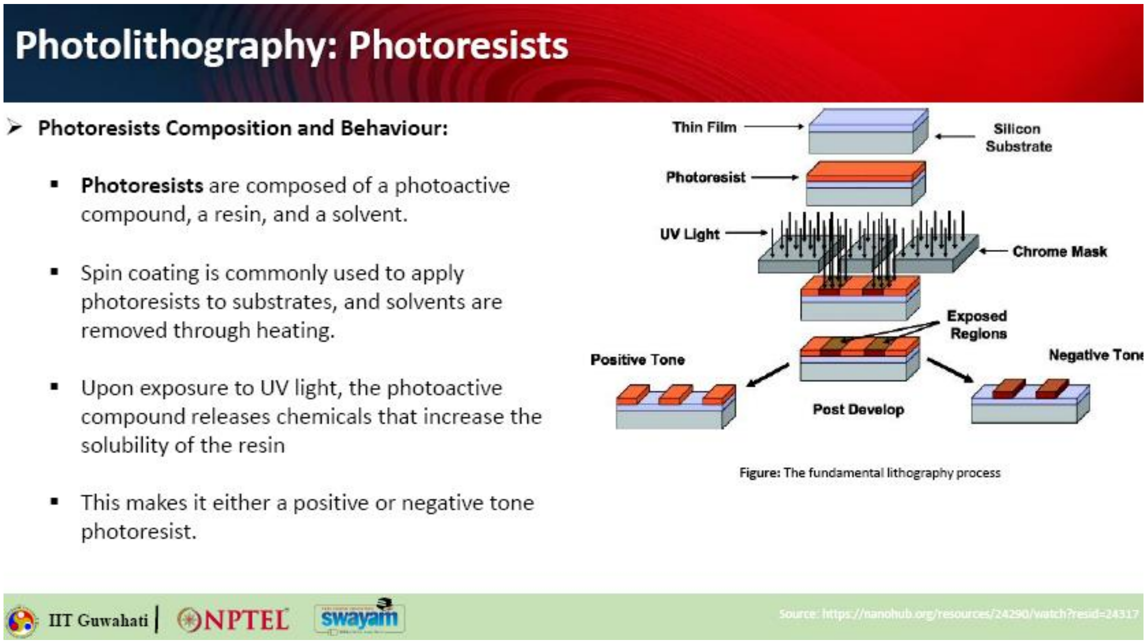
It is a type of laser that generates intense ultraviolet light via the use of excited dimers or molecules. Unlike most lasers that rely on stimulated emission from atoms or ions excimer lasers use a combination of noble gases and reactive gases to create a laser medium. So extreme UV sources are also under development which operate at 13.5 nanometer so they will be used for advanced lithography applications. Now in lithography it is crucial to ensure uniform illumination intensity across the entire substrate surface which requires shaping the beam into a flat speckle free pattern to avoid undesirable effects.

So this is one of the requirement of getting a good lithography photolithography. So when you when we talk about speckle free pattern so speckle free pattern is basically referring to the desired outcome of the lithographic process where the pattern or the image that is produced on the photosynthetic photosensitive material or photoresist is free from the speckles or unwanted noise you can say. So speckles when you think of speckles in lithographic pattern they can degrade the quality and the precision of the final image especially in applications where you actually aim for high resolution okay such as in semiconductor manufacturing. So those are the cases you need to make sure that uniform illumination intensity is available across the entire substrate surface. So, this is typically the process of lithography as you can see you have a silicon substrate and you have a thin film deposited on this.



Photolithography: Photoresists

➢ **Photoresists Composition and Behaviour:**

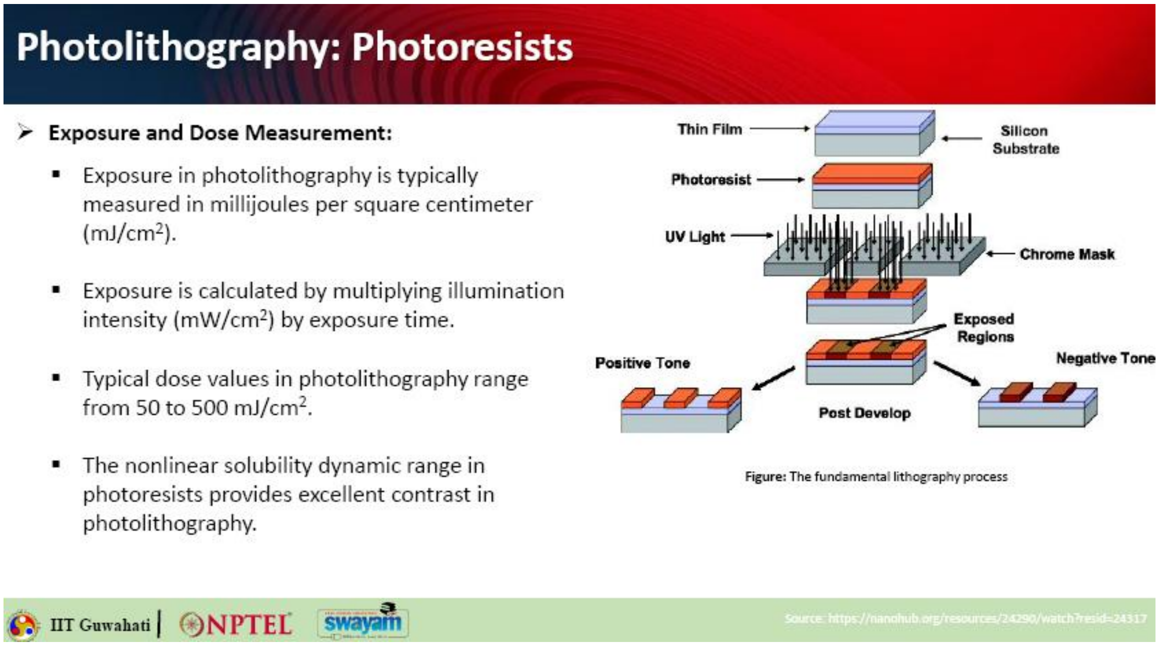
- **Photoresists** are composed of a photoactive compound, a resin, and a solvent.
- Spin coating is commonly used to apply photoresists to substrates, and solvents are removed through heating.
- Upon exposure to UV light, the photoactive compound releases chemicals that increase the solubility of the resin
- This makes it either a positive or negative tone photoresist.

Figure: The fundamental lithography process

Source: https://nanohub.org/resources/24290/watch?resid=24317

So we have discussed the methods of thin film deposition in the previous lecture. Now after that you can spin coat a photoresist that is a chemical and then you have this particular chrome mask it is a mask made of chromium. So you can see there are openings in the mask and then when you expose UV light to it UV light rays are blocked to where the metal parts are there but it can actually go through onto your photoresist where the masks are open okay and that way you get this exposed regions okay. Now if these are positive photoresist when you develop it by etching out this particular things you will see that when you develop a positive photoresist this parts actually disappear or they dissolve so you are left with this particular pattern whereas if these are negative tone photoresist you will see that this only remains the remaining parts actually dissolve okay. So as you understand here the photoresist basically composed of a photo active compound a resin and a solvent and how do you apply photoresist as I mentioned spin coating is commonly used to apply photoresist on the substrates and solvents are removed through heating and once you expose them to UV light the photo active compound it releases chemicals that increase the solubility of the resin.

So it makes it either positive or negative tone photoresist. So once again if you have positive tone photoresist this exposed patterns are dissolved they can be removed and if they are negative tone photoresist this particular patterns they stay and the remaining photoresist can be dissolved okay. So there are important parameters in this process something like what should be the exposure the light exposure and the dosage okay. So you can see the exposure in photolithography is typically measured in milli joules per centimeter square and exposure is calculated by multiplying the illumination intensity that is given by milli watt per centimeter square by the exposure time. So that gives you the exposure and the typical dose value for photolithography ranges from 50 to 500 milli joule per centimeter square.



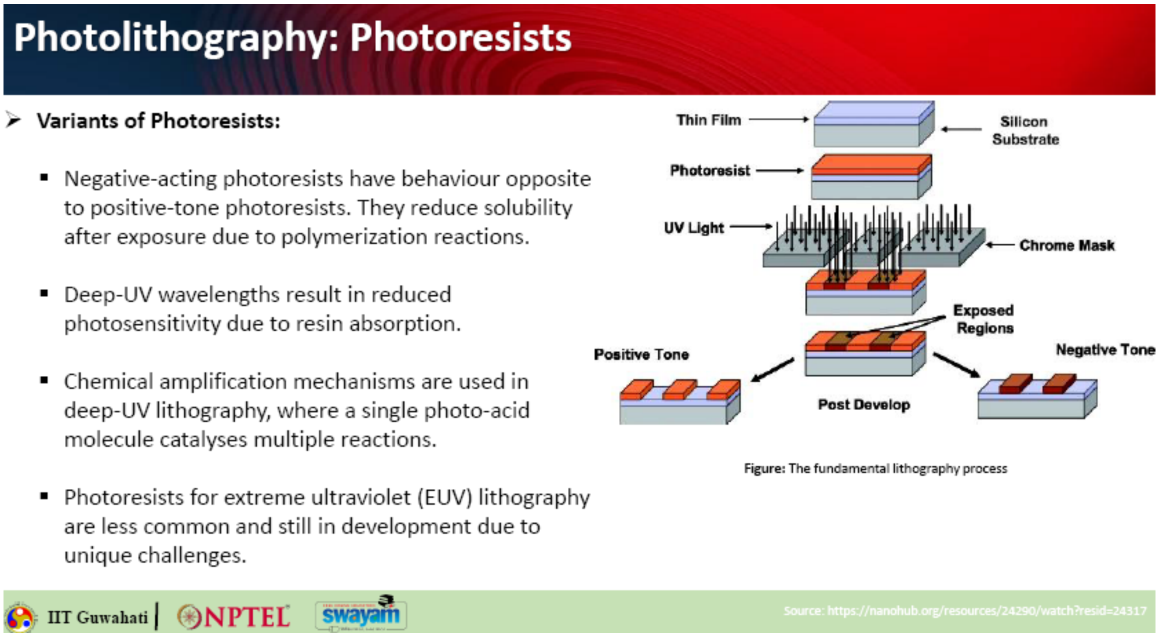
Photolithography: Photoresists

- **Exposure and Dose Measurement:**
  - Exposure in photolithography is typically measured in millijoules per square centimeter (mJ/cm^2).
  - Exposure is calculated by multiplying illumination intensity (mW/cm^2) by exposure time.
  - Typical dose values in photolithography range from 50 to 500 mJ/cm^2.
  - The nonlinear solubility dynamic range in photoresists provides excellent contrast in photolithography.

Figure: The fundamental lithography process

Source: https://nanohub.org/resources/24290/watch?resid=24317

So that is the range of the exposure that is needed for photolithography applications. And the nonlinear solubility dynamic range in photoresist provides this excellent contrast in photolithography and as you can see here. And when you talk about photoresist there are two types so one is positive one is negative so the negative acting photoresist they behave completely opposite to the positive tone photoresist. So in the case of negative tone they reduce the solubility after exposure due to some polymerization reaction so they do not get dissolved when you try to develop them the remaining parts get dissolved okay. So deep UV wavelengths result in reduced photosensitivity due to resin absorption and chemical amplification mechanisms can be used in deep UV lithography where a single photo acid molecule catalyzes multiple reactions.



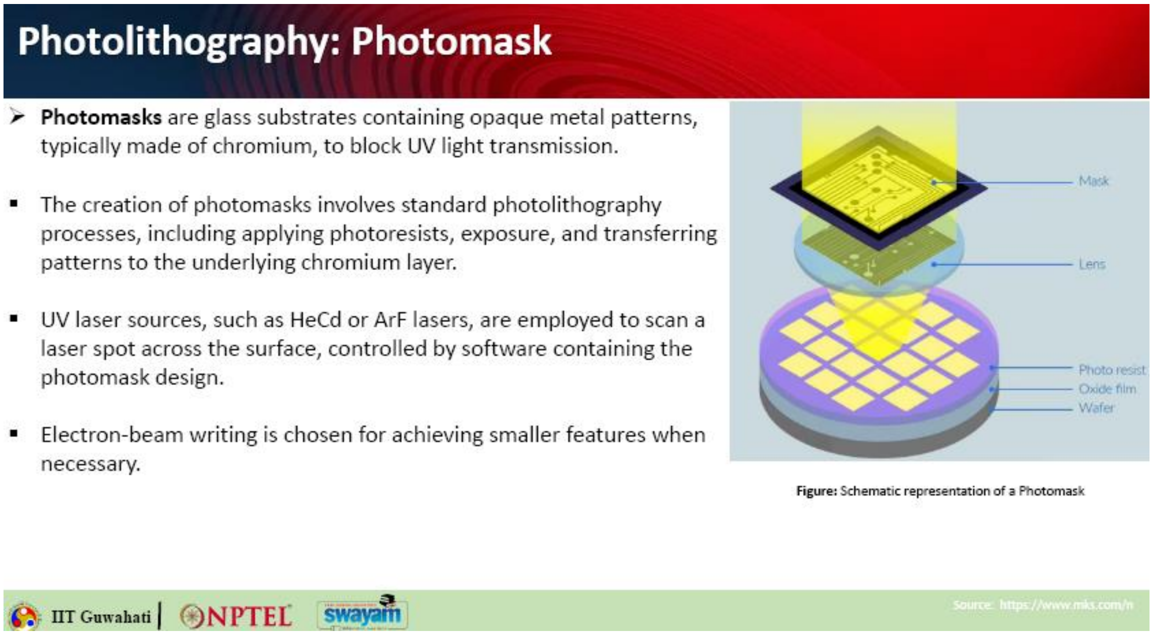
Photolithography: Photoresists

- **Variants of Photoresists:**
  - Negative-acting photoresists have behaviour opposite to positive-tone photoresists. They reduce solubility after exposure due to polymerization reactions.
  - Deep-UV wavelengths result in reduced photosensitivity due to resin absorption.
  - Chemical amplification mechanisms are used in deep-UV lithography, where a single photo-acid molecule catalyses multiple reactions.
  - Photoresists for extreme ultraviolet (EUV) lithography are less common and still in development due to unique challenges.

Figure: The fundamental lithography process

Source: https://nanohub.org/resources/24290/watch?resid=24317

And photoresist for extreme ultraviolet lithography are less common but they are still in development due to the unique challenges. So you can understand that extreme UV lithography is still not very popular because the material that can help this particular technique is still under development. Whereas the UV lithography once are well developed even the deep UV lithography once are also available. Another important component that you have seen in this process of lithography is the mask okay. It is it you can call it simply mask photo mask or it is chrome mask okay.



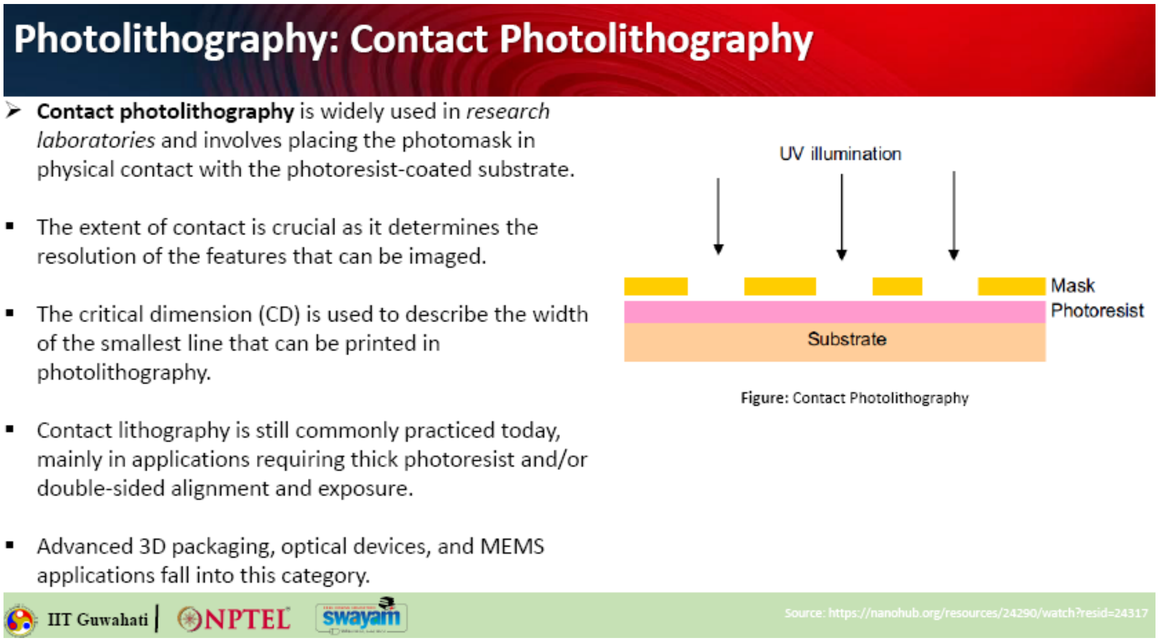
Photolithography: Photomask

- **Photomasks** are glass substrates containing opaque metal patterns, typically made of chromium, to block UV light transmission.
- The creation of photomasks involves standard photolithography processes, including applying photoresists, exposure, and transferring patterns to the underlying chromium layer.
- UV laser sources, such as HeCd or ArF lasers, are employed to scan a laser spot across the surface, controlled by software containing the photomask design.
- Electron-beam writing is chosen for achieving smaller features when necessary.

Figure: Schematic representation of a Photomask

Source: https://www.mks.com/n

So what are masks? Masks are basically these are glass substrates which contain opaque metallic patterns and these patterns are typically made of chromium which are supposed to block the UV transmission okay. So, the creation of photo masks involved standard photolithography process including applying photoresist, exposure and patterning the patterns of the underlying chromium layer. So that way you obtain one mask and then you can use that mask to create many such replicas right. And UV laser source such as helium cadmium or argon fluoride lasers this kind of lasers can be employed to scan a laser spot across the surface and this is typically controlled by software which contains the photo mask design. So here also you can see the mask is there then you have a lens which are actually focus it on this particular chip area and what is this? This is basically a photoresist below that you have the oxide film and then you have the wafer.



Photolithography: Contact Photolithography

- **Contact photolithography** is widely used in *research laboratories* and involves placing the photomask in physical contact with the photoresist-coated substrate.
- The extent of contact is crucial as it determines the resolution of the features that can be imaged.
- The critical dimension (CD) is used to describe the width of the smallest line that can be printed in photolithography.
- Contact lithography is still commonly practiced today, mainly in applications requiring thick photoresist and/or double-sided alignment and exposure.
- Advanced 3D packaging, optical devices, and MEMS applications fall into this category.

Figure: Contact Photolithography

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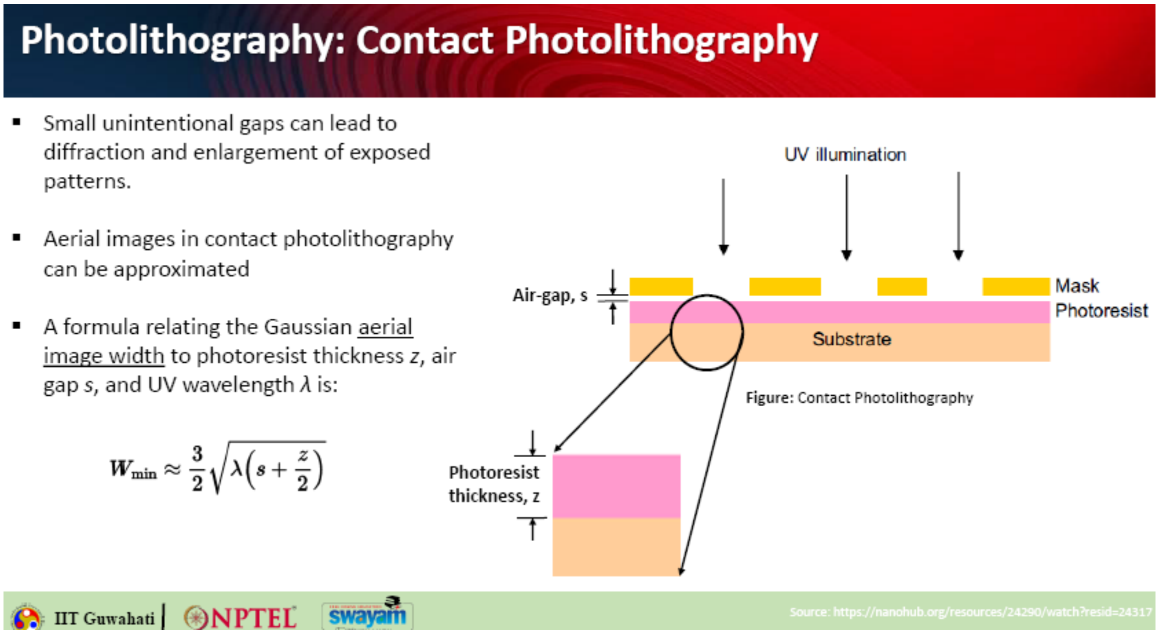
Source: https://nanohub.org/resources/24290/watch?resid=24317

So electron beam writing is chosen for achieving smaller features when necessary. So that you will see that you know that with lithography, photolithography the minimum feature size as you can understand is diffraction limited lambda by 2. So when you use electron beam writing you can actually reduce the smaller feature size okay or you can go down to even further smaller sizes. The next method that you can think of is this contact photolithography. So what happens in contact photolithography? So, you have a substrate, you have a photoresist on this and then you have a mask and this you are actually doing UV illumination.

So this contact photolithography technique is widely used in research labs and it involves placing the photo mask in physical contact with the photoresist coated substrate. So here you see there is no physical contact right the mask and then there is a lens and then you are just doing focusing so it is not actually the mask is not touching your photoresist coated substrate but here it does okay. So the extent of contact is critical as it determines the resolution of the feature that can be imaged okay. So when you put it on top the resolution matters. The critical dimension is used to describe the width of the smallest line that can be printed in this kind of photolithography.

So that is called the critical dimension. So where this contact photolithography is used? They are commonly used or practiced today also mainly in the applications which require thick photoresist or double sided alignment and exposure. Some examples could be in advanced 3D packaging, optical devices, MEMS applications etc. Now there could be some small unintentional gaps between the mask and the photoresist as you see here there is a small air gap s okay and that could lead to diffraction and enlargement of the exposed patterns okay. That is something you do not like okay because you are actually looking for finer resolution.



Photolithography: Contact Photolithography

- Small unintentional gaps can lead to diffraction and enlargement of exposed patterns.
- Aerial images in contact photolithography can be approximated
- A formula relating the Gaussian aerial image width to photoresist thickness z, air gap s, and UV wavelength λ is:

$$W_{\min} \approx \frac{3}{2}\sqrt{\lambda\left(s+\frac{z}{2}\right)}$$

Figure: Contact Photolithography

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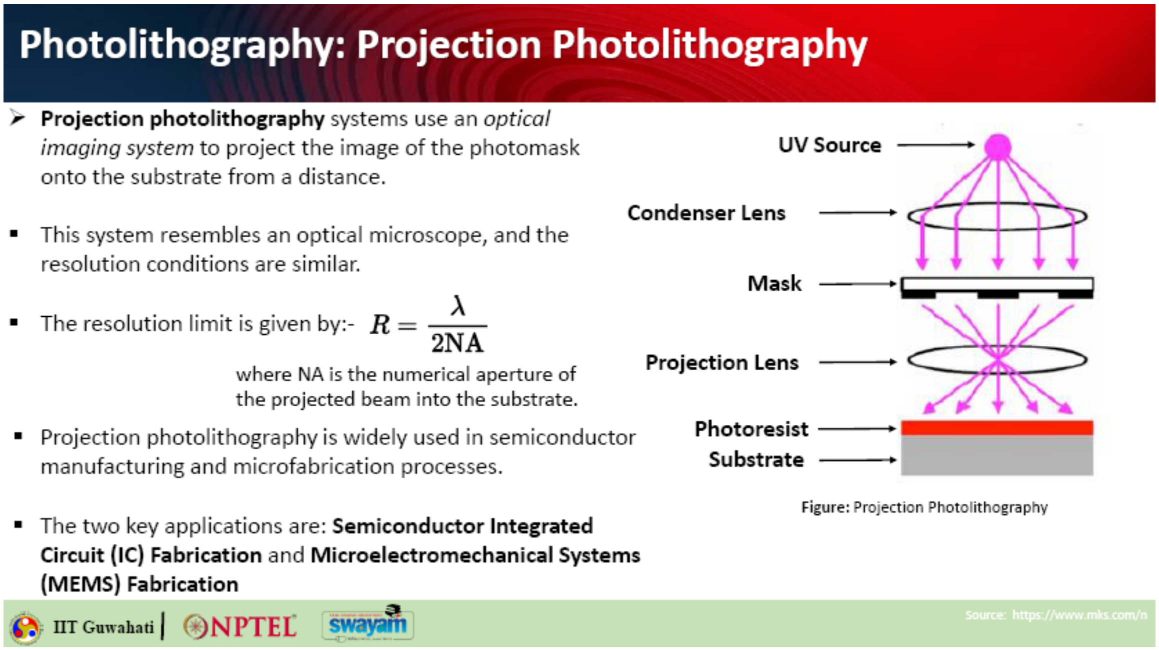
Source: https://nanohub.org/resources/24290/watch?resid=24317

Now you can do aerial images in contact photolithography which can be approximated. There is a formula that relates the Gaussian aerial image width to the photoresist thickness. So the thickness of this photoresist layer is z okay the air gap is s and the UV light wavelength if it is lambda you can find out what is the width of the aerial image of the pattern that you have developed. So, w_{min} will be typically $W_{min} \approx \frac{3}{2}\sqrt{\lambda\left(s+\frac{z}{2}\right)}$ okay that gives you a formula so that relates the Gaussian aerial image width and you can see it is basically related with this air gap and also the photoresist thickness okay. So, the next type of photolithography technique is called projection photolithography.



Photolithography: Projection Photolithography

- **Projection photolithography** systems use an *optical imaging system* to project the image of the photomask onto the substrate from a distance.
- This system resembles an optical microscope, and the resolution conditions are similar.
- The resolution limit is given by:- $R = \dfrac{\lambda}{2\text{NA}}$

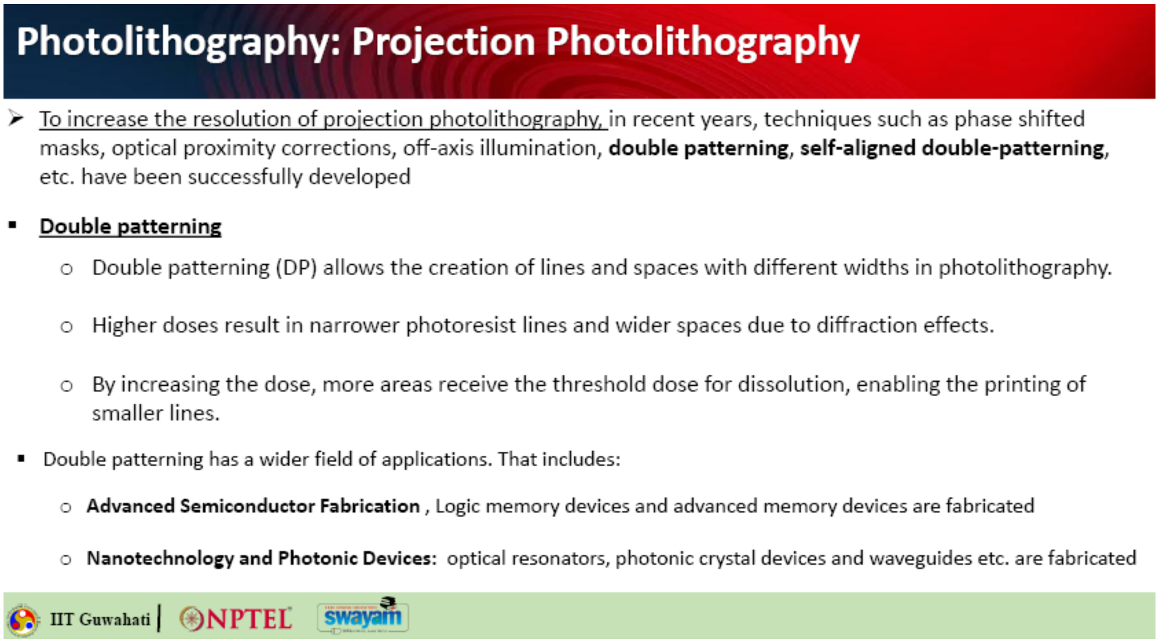
  where NA is the numerical aperture of the projected beam into the substrate.
- Projection photolithography is widely used in semiconductor manufacturing and microfabrication processes.
- The two key applications are: **Semiconductor Integrated Circuit (IC) Fabrication** and **Microelectromechanical Systems (MEMS) Fabrication**

Figure: Projection Photolithography

Source: https://www.mks.com/n

The name itself tells you that you are not actually putting the mask in the contact of the photoresist anymore you are trying to use kind of a lens projection lens as you see here to do some kind of projection on the photoresist. So that is how the name has come right. So for projection photolithography systems use an optical imaging system to project the image of the photomask onto the substrate from a distance. So this is kind of popular where you cannot actually go and contaminate the substrate okay. So this kind of system resembles an optical microscope and the resolution conditions are similar to that.

However, the resolution here will be limited by the numerical aperture of the projected beam onto the substrate. So R the resolution limit can be set by lambda by 2 NA. So why they are used? They are popularly used in semiconductor manufacturing and micro fabrication processes and key applications as you can see these are in IC fabrication and MEMS fabrication. So this is a very very commonly used technique called projection photolithography. Now what do you do to increase the resolution? You can see here that there is some limit on the resolution which is coming from the numerical aperture okay of the projected beam onto the substrate.



Photolithography: Projection Photolithography

- To increase the resolution of projection photolithography, in recent years, techniques such as phase shifted masks, optical proximity corrections, off-axis illumination, **double patterning**, **self-aligned double-patterning**, etc. have been successfully developed

- **Double patterning**
  - Double patterning (DP) allows the creation of lines and spaces with different widths in photolithography.
  - Higher doses result in narrower photoresist lines and wider spaces due to diffraction effects.
  - By increasing the dose, more areas receive the threshold dose for dissolution, enabling the printing of smaller lines.
- Double patterning has a wider field of applications. That includes:
  - **Advanced Semiconductor Fabrication** , Logic memory devices and advanced memory devices are fabricated
  - **Nanotechnology and Photonic Devices:** optical resonators, photonic crystal devices and waveguides etc. are fabricated

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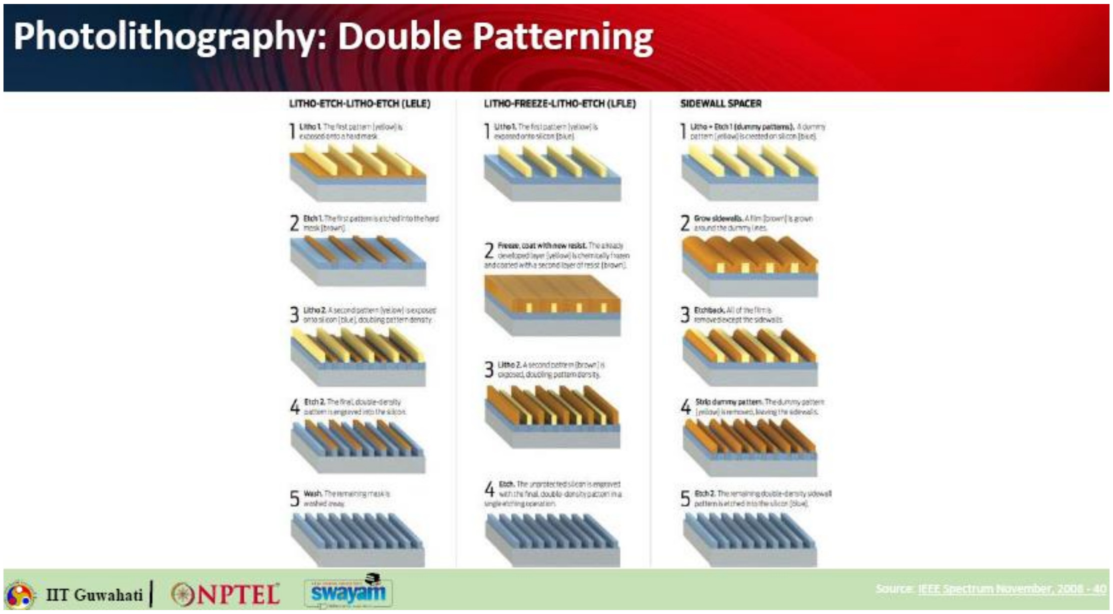
So in order to increase the resolution of projection photolithography recently there are different techniques been invented which are like phase shifted mask or optical proximity corrections, off axis elimination, double patterning, self aligned double patterning etc. So we will not go into all these techniques but we just want to discuss about double patterning technique here because that is very very popularly used. So double patterning allows the creation of lines and spaces with different widths in the photolithography. So higher doses result in narrower photoresist lines and wider spaces due to diffraction effects and by increasing the dose more areas will receive the threshold dose for dissolution enabling the printing of smaller lines. And double patterning has a wider range of application so they can be used for advanced semiconductor manufacturing or fabrication you can say.

So examples such as logic memory devices or advanced memory devices can be fabricated using this technique. They can also be used for nanotechnology and photonic devices so they are very relevant to us okay in this particular course what you have understood they can be used for optical resonator photonic crystal devices and waveguides. So, you can use double patterning for this one.



Photolithography: Double Patterning

LITHO-ETCH-LITHO-ETCH (LELE)

1 **Litho 1.** The first pattern (yellow) is exposed onto a hard mask.

2 **Etch 1.** The first pattern is etched into the hard mask (brown).

3 **Litho 2.** A second pattern (yellow) is exposed onto silicon (blue), doubling pattern density.

4 **Etch 2.** The final, double-density pattern is engraved into the silicon.

5 **Wash.** The remaining mask is washed away.

LITHO-FREEZE-LITHO-ETCH (LFLE)

1 **Litho 1.** The first pattern (yellow) is exposed onto silicon (blue).

2 **Freeze, coat with new resist.** The already developed layer (yellow) is chemically frozen and coated with a second layer of resist (brown).

3 **Litho 2.** A second pattern (brown) is exposed, doubling pattern density.

4 **Etch.** The unprotected silicon is engraved with the final, double-density pattern in a single etching operation.

SIDEWALL SPACER

1 **Litho + Etch 1 (dummy patterns).** A dummy pattern (yellow) is created on silicon (blue).

2 **Grow sidewalls.** A film (brown) is grown around the dummy lines.

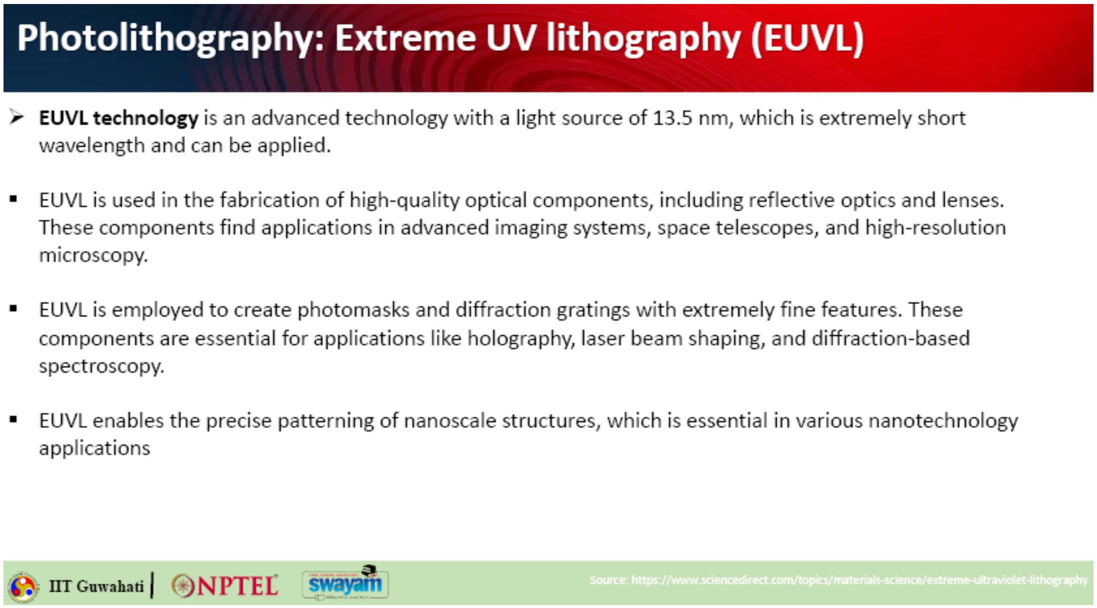
3 **Etchback.** All of the film is removed except the sidewalls.

4 **Strip dummy pattern.** The dummy pattern (yellow) is removed, leaving the sidewalls.

5 **Etch 2.** The remaining double-density sidewall pattern is etched into the silicon (blue).

Source: IEEE Spectrum November, 2008 - 40

So, there are different methods in double patterning so let us look into these three different techniques those are used. The first one is called LELE. So it is litho etch litho etch technique or LELE technique. So what happens in this particular case so you first do the litho one that is the first step so the first pattern which is in yellow is exposed onto a hard mask and then you etch the first pattern is etched onto the hard mask so you get this particular brown shape patterns. Then you bring the second mask so this is you are doing the second lithography. A second pattern which is again in yellow is exposed onto the silicon that is shown in blue color and that actually doubles the pattern density.



Photolithography: Extreme UV lithography (EUVL)

- **EUVL technology** is an advanced technology with a light source of 13.5 nm, which is extremely short wavelength and can be applied.

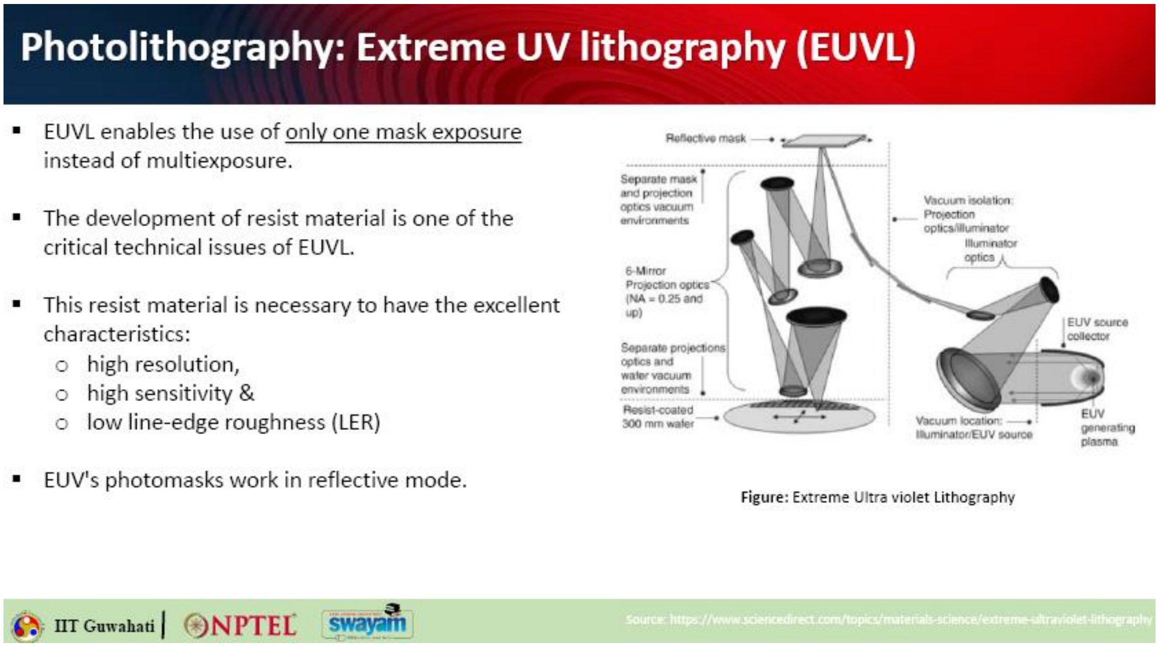
- EUVL is used in the fabrication of high-quality optical components, including reflective optics and lenses. These components find applications in advanced imaging systems, space telescopes, and high-resolution microscopy.

- EUVL is employed to create photomasks and diffraction gratings with extremely fine features. These components are essential for applications like holography, laser beam shaping, and diffraction-based spectroscopy.

- EUVL enables the precise patterning of nanoscale structures, which is essential in various nanotechnology applications

Source: https://www.sciencedirect.com/topics/materials-science/extreme-ultraviolet-lithography

So, this is how you are actually improving the resolution of this technique by doing double patterning. So, this is how you are doing two times the lithography and that gives you higher density. And then after this litho you again do etching the final double density pattern is then etched into the substrate as you can see here. And the remaining mask which are here that can be washed away and you can get this double patterned array. So this particular technique is called litho etch litho etch technique or LELE technique. The second one is called litho freeze litho etch technique LFLE.



Photolithography: Extreme UV lithography (EUVL)

- EUVL enables the use of only one mask exposure instead of multiexposure.
- The development of resist material is one of the critical technical issues of EUVL.
- This resist material is necessary to have the excellent characteristics:
  - high resolution,
  - high sensitivity &
  - low line-edge roughness (LER)
- EUV's photomasks work in reflective mode.

Figure: Extreme Ultra violet Lithography

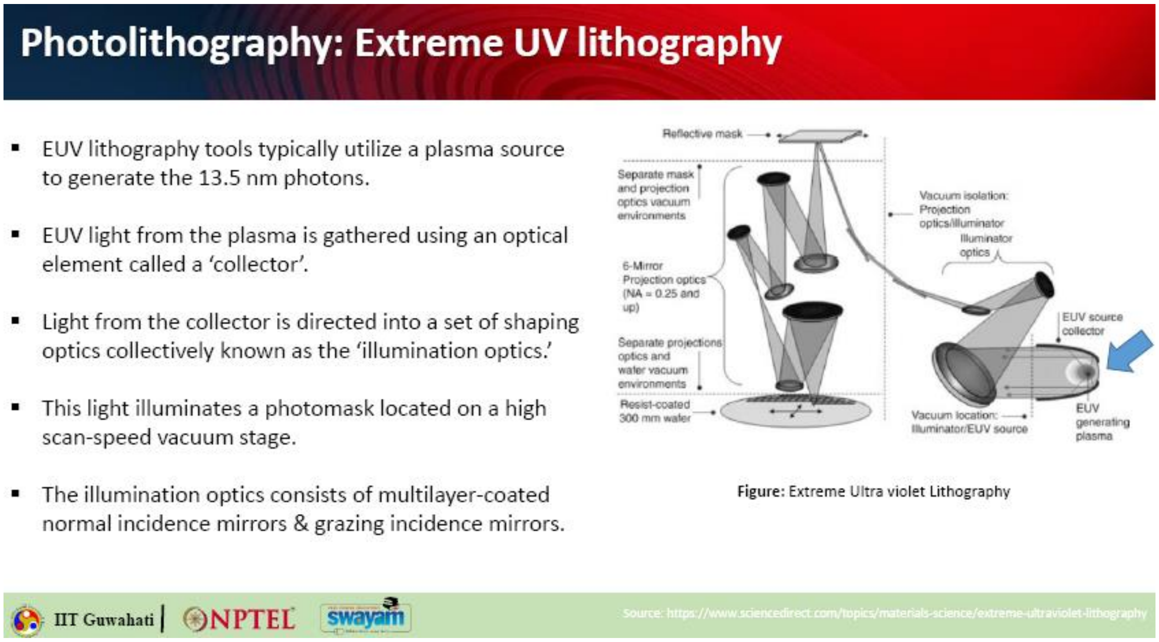
Source: https://www.sciencedirect.com/topics/materials-science/extreme-ultraviolet-lithography

So here also the first step looks similar so you have a litho one step the first pattern which is shown in yellow is exposed onto the silicon that is the blue one here. And then you do the freeze step so here the second step is basically freeze and you coat with a new resist. So what happens in this case the already developed layer that is shown in yellow is chemically frozen and coated with the second layer of resist which is shown in this brown color. And then you do the litho step again so the second pattern which is shown in brown is then exposed and that doubles the pattern density. And in the final step you etch again so you remove the unprotected silicon with this final double density pattern in a single etching operation.

So you just do one etching and you can get this double density pattern. So this method is called litho freeze litho etch method. There is also another method called sidewall spacer. So here you do in the first step you do litho plus etch1 of the dummy patterns. So what you do a dummy pattern shown in yellow is basically created on this blue silicon layer.

And then you grow sidewalls. So a film that is shown in brown is grown around the dummy lines that you see here and then you do the etch back. So all the films are removed except the sidewalls. So the sidewalls are remaining like this then you strip the dummy pattern that is the yellow pattern is now removed and leaving only the sidewalls.

So you have got this you know sidewalls so and then you can do the etching second etching and that will give you this double etched or you can say the double density array. So, the remaining double density sidewall pattern is etched onto the silicon substrate and you will get so from here you can get the double density pattern on the silicon.



Photolithography: Extreme UV lithography

- EUV lithography tools typically utilize a plasma source to generate the 13.5 nm photons.
- EUV light from the plasma is gathered using an optical element called a 'collector'.
- Light from the collector is directed into a set of shaping optics collectively known as the 'illumination optics.'
- This light illuminates a photomask located on a high scan-speed vacuum stage.
- The illumination optics consists of multilayer-coated normal incidence mirrors & grazing incidence mirrors.

Figure: Extreme Ultra violet Lithography

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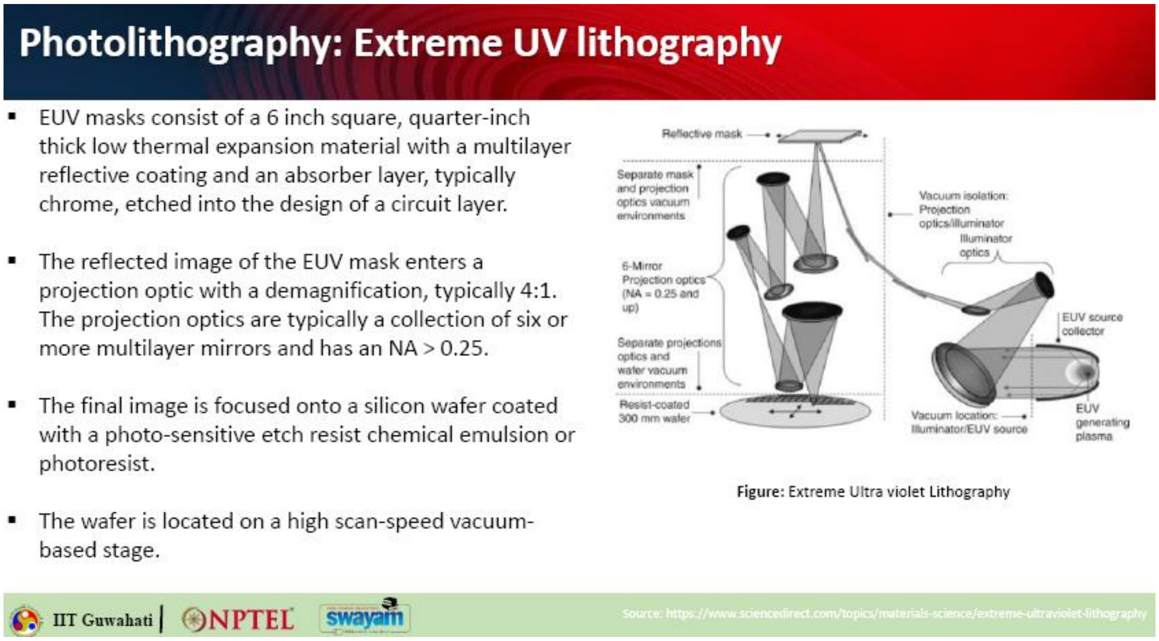
Source: https://www.sciencedirect.com/topics/materials-science/extreme-ultraviolet-lithography

So these are three methods of increasing or doubling the pattern density on a silicon wafer. So this is very commonly used technique so this is why we have gone into bit of details of this particular technique. Now what is another method of using increasing the resolution you can think of increase ah reducing the wavelength of the light that is being used. So, in that case extreme UV lithography becomes very very common approach because you can use there a light source of 13.5 nanometer and it is an extremely short wavelength and that can give you a very fine resolution.



Photolithography: Extreme UV lithography

- EUV masks consist of a 6 inch square, quarter-inch thick low thermal expansion material with a multilayer reflective coating and an absorber layer, typically chrome, etched into the design of a circuit layer.
- The reflected image of the EUV mask enters a projection optic with a demagnification, typically 4:1. The projection optics are typically a collection of six or more multilayer mirrors and has an NA > 0.25.
- The final image is focused onto a silicon wafer coated with a photo-sensitive etch resist chemical emulsion or photoresist.
- The wafer is located on a high scan-speed vacuum-based stage.

Figure: Extreme Ultra violet Lithography

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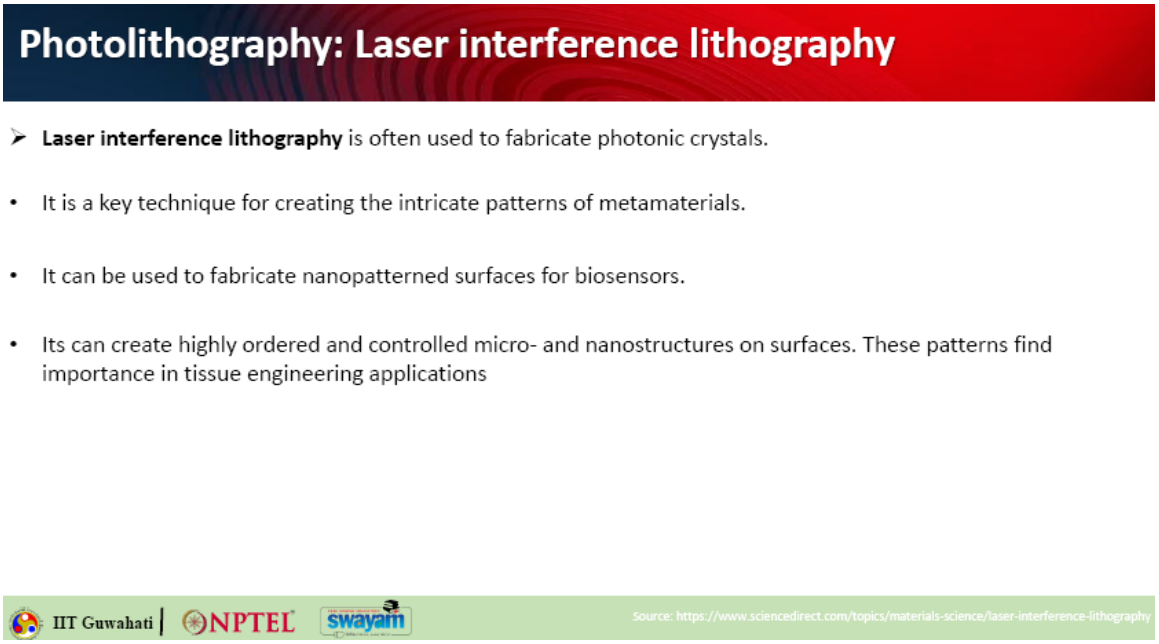
Source: https://www.sciencedirect.com/topics/materials-science/extreme-ultraviolet-lithography

So EUVL that is extreme UV lithography is basically used for fabrication of high quality optical components which are used in reflective optics and lenses and they find applications in advanced imaging systems, space telescopes, very high resolution microscopes and all these things. EUVL is basically employed to create photo masks, diffraction grating with extremely fine features and these components are essential for applications such as lithography, laser beam shaping, diffraction based spectroscopy etc. This technique also enables precise patterning of nano scale structures so that makes it very very essential in nanotechnology applications. So this technique uses only one mask exposure instead of multiple exposure and the development of the resist material is one of the critical technical issue in this case as we discussed because there has to be some material which is sensitive to this particular wavelength. So that is the challenge currently and this material resist material is necessary to have excellent characteristics like high resolution, high sensitivity, low line edge, roughness etc.

And remember that in this lithography the photo masks work in reflective mode. So the photo masks used in extreme UV lithography they work in reflective mode. So let us look into the setup of extreme ultraviolet lithography. So here you can see in this diagram that extreme UV lithography tool typically utilize a plasma source to generate the 13.5 nanometer photons as you can see here and the light from the plasma is then gathered using an optical element called collector.



Photolithography: Laser interference lithography

- **Laser interference lithography** is often used to fabricate photonic crystals.
- It is a key technique for creating the intricate patterns of metamaterials.
- It can be used to fabricate nanopatterned surfaces for biosensors.
- Its can create highly ordered and controlled micro- and nanostructures on surfaces. These patterns find importance in tissue engineering applications

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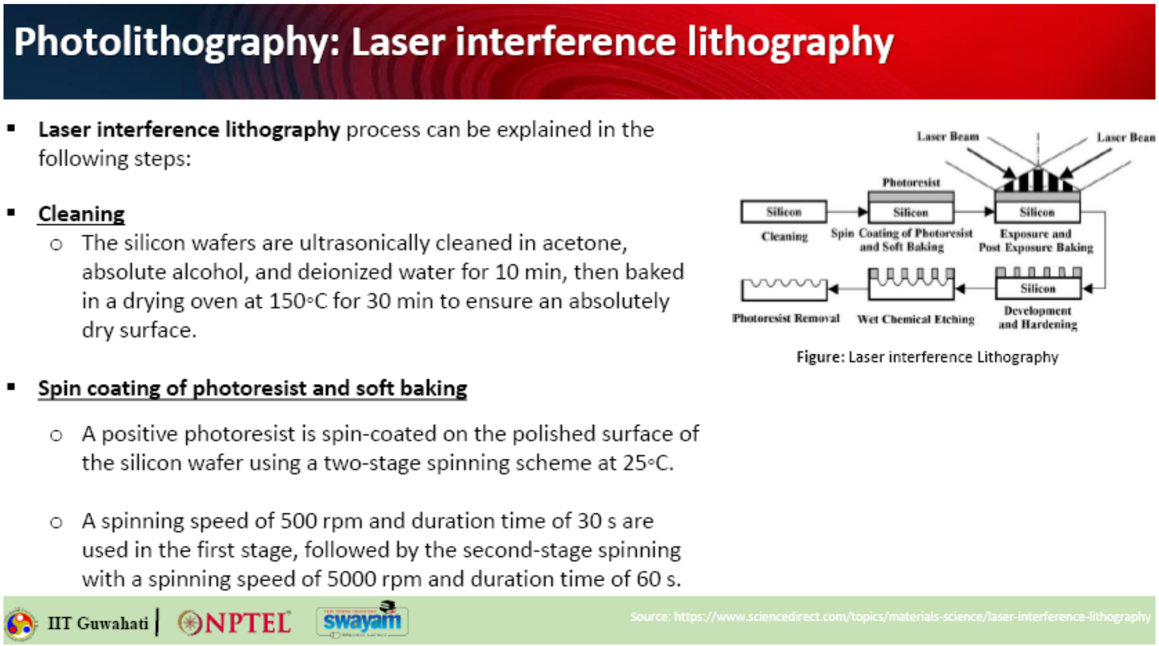
Source: https://www.sciencedirect.com/topics/materials-science/laser-interference-lithography

So these collectors they gather the light and then the light is directed into a set of shaping optics elements like you have got a mirror here and then this. So this one are also called illumination optics as you see. So it goes here gets reflected to this mirror it goes here so this part is called illumination optics and the light illuminates a photo mask as you see here there is a photo mask which is located on a high scan speed vacuum stage. So this is the vacuum isolation so this part is in vacuum. So, it actually moves in this high scan speed vacuum stage and then from here it reflects and undergoes multiple reflection and finally it is being put on this resist coated wafer to make this pattern.



Photolithography: Laser interference lithography

- **Laser interference lithography** process can be explained in the following steps:
- Cleaning
  - The silicon wafers are ultrasonically cleaned in acetone, absolute alcohol, and deionized water for 10 min, then baked in a drying oven at 150°C for 30 min to ensure an absolutely dry surface.
- Spin coating of photoresist and soft baking
  - A positive photoresist is spin-coated on the polished surface of the silicon wafer using a two-stage spinning scheme at 25°C.
  - A spinning speed of 500 rpm and duration time of 30 s are used in the first stage, followed by the second-stage spinning with a spinning speed of 5000 rpm and duration time of 60 s.

Figure: Laser interference Lithography

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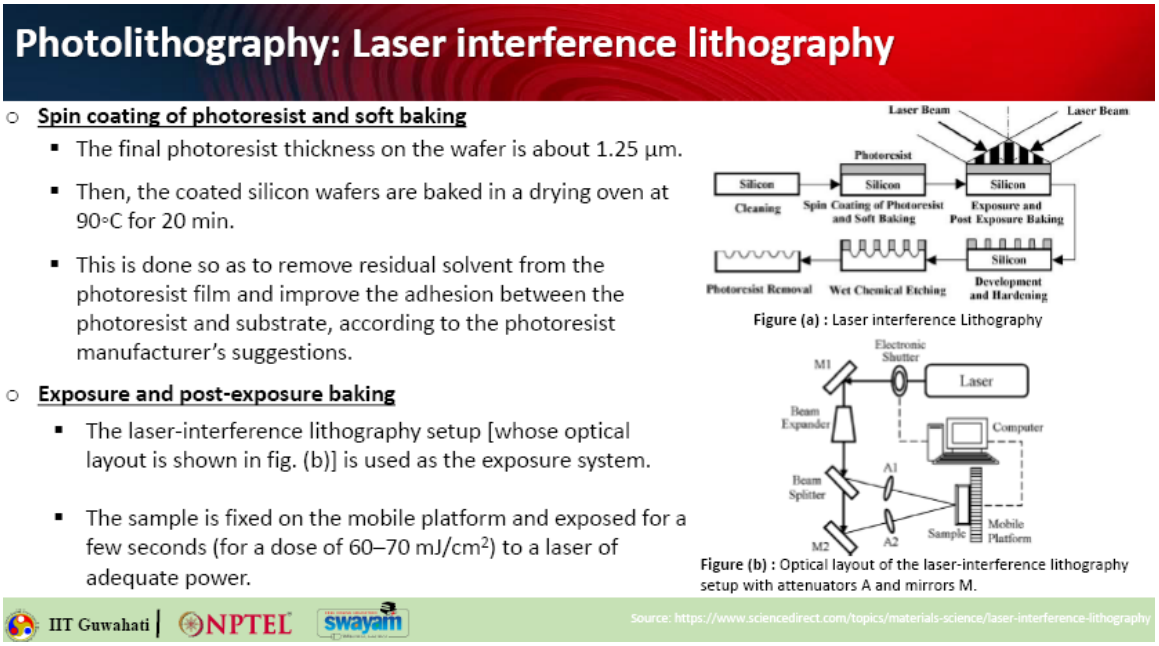
Source: https://www.sciencedirect.com/topics/materials-science/laser-interference-lithography

Now the illumination optics that you see here it consists of multi-layer coated normal incidence mirrors and also grazing incidence mirrors. And the mask that you see this mask is basically a 6 inch square, quarter inch thick low thermal expansion material which has got multiple multi-layer reflective coating and also an observable layer typically which is made of chrome and it is etched into the design of a circuit layer. So what happens the reflected image of this mask enters a projection optics so you can actually call this part as projection optics and this gives you a demagnification typically 4 is to 1 and the projection optics are typically a collection of 6 or more multi-layer mirrors and they have typically any numerical aperture more than 0.25. And the final image that you see here is focused onto a silicon wafer coated with a photosensitive etch resist chemical emulsion or simply photoresist.

So this part also is located on a high scan speed vacuum stage vacuum based stage so this is where the wafer will be positioned. So here you can see this part basically gives you the shows you the vacuum isolation okay so this is also in vacuum. Now where this is useful we have discussed so this is useful in getting very very thin patterns or narrow patterns because the wavelength that you are using is only 13.5 nanometer. There is another type of lithography method that helps you in achieving your desired resolution that is called laser interference lithography.

So this kind of lithography is typically used to fabricate photonic crystals and it is a key technique for creating intricate patterns of metamaterials. So for the topics discussed in this course we can see that laser interference lithography looks pretty much applicable. It can also be used to fabricate nanopattern surfaces for biosensors okay. It can create highly ordered and controlled micro and nano structures on surfaces and this patterns will find importance in tissue engineering applications as well. So, let us go into a bit more details of this particular technique because this is very much relevant to the devices we have discussed in this course.



Photolithography: Laser interference lithography

- **Spin coating of photoresist and soft baking**
  - The final photoresist thickness on the wafer is about 1.25 µm.
  - Then, the coated silicon wafers are baked in a drying oven at 90◦C for 20 min.
  - This is done so as to remove residual solvent from the photoresist film and improve the adhesion between the photoresist and substrate, according to the photoresist manufacturer's suggestions.
- **Exposure and post-exposure baking**
  - The laser-interference lithography setup [whose optical layout is shown in fig. (b)] is used as the exposure system.
  - The sample is fixed on the mobile platform and exposed for a few seconds (for a dose of 60–70 mJ/cm^2) to a laser of adequate power.

Figure (a) : Laser interference Lithography

Figure (b) : Optical layout of the laser-interference lithography setup with attenuators A and mirrors M.

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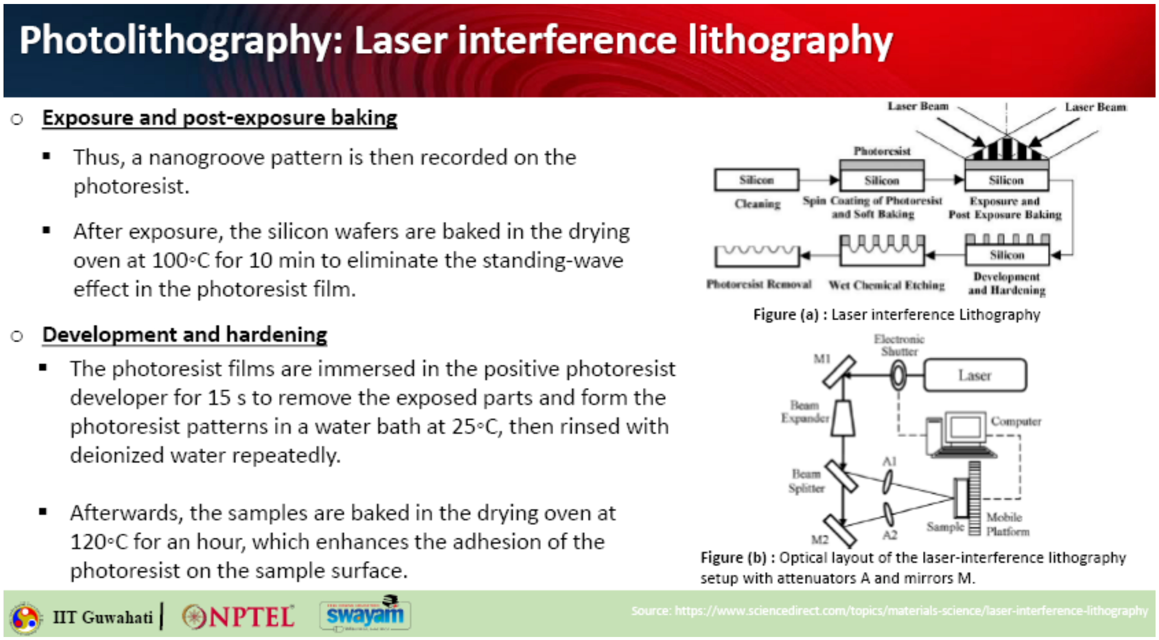
Source: https://www.sciencedirect.com/topics/materials-science/laser-interference-lithography

So let us start with the first process that is cleaning of the silicon wafer. So you can see the silicon wafers are ultrasonically cleaned in acetone absolute alcohol and deionized water for 10 minutes and then it is baked in a drying oven at 150 degree Celsius for 30 minutes to ensure it is an absolutely dry surface. And after that you go on to the spin coating stage where you are supposed to spin coat the photoresist and do some soft baking. So here a positive photoresist is spin coated on the polished surface of the silicon wafer using a two stage spinning scheme and it is done at 25 degree centigrade and you use the spinning speed of 500 rpm and the duration for 30 second for the first stage and then you do the second stage spinning where the spin speed is 10 times that is 5000 rpm and you do it for 60 seconds. So that is how you do the spin coating and then you actually do the soft baking.

So what you see the final photoresist thickness on the wafer is about 1.25 micron. So this is the height you have to achieve for the photoresist and then you can put the coated silicon wafer into a drying oven at 90 degree centigrade for 20 minute for this soft baking process. And this is done to remove any residual solvent from the photoresist film and it also improves the adhesion between the photoresist and the substrate and it is typically done according to the photoresist manufacturer's suggestions. So they actually can tell you what is the process for this particular photoresist chemical to bind very strongly with your silicon substrate and you got to follow those process.

After that you can go look into the third stage which is basically exposure and post exposure baking. So here you can see that the laser interference lithography setup is shown typically like this. So this is the setup that you can see laser beams are coming from two sides and then they are interfering and this is typically the substrate and here also you can see this is the sample you have got a laser which has got a electronic shutter it comes from a mirror one it gets reflected there is a beam expander and then there is a beam splitter. So one part of the beam is coming this way the remaining part goes this way from another mirror it gets reflected and you actually generate two laser beams and that actually focuses at one point where you can create this interference patterns. So, the sample is fixed on a mobile platform and it is exposed for few seconds so typical dosage is 60 to 70 milli joule per centimeter square to a laser of adequate power.



Photolithography: Laser interference lithography

- **Exposure and post-exposure baking**
  - Thus, a nanogroove pattern is then recorded on the photoresist.
  - After exposure, the silicon wafers are baked in the drying oven at 100◦C for 10 min to eliminate the standing-wave effect in the photoresist film.
- **Development and hardening**
  - The photoresist films are immersed in the positive photoresist developer for 15 s to remove the exposed parts and form the photoresist patterns in a water bath at 25◦C, then rinsed with deionized water repeatedly.
  - Afterwards, the samples are baked in the drying oven at 120◦C for an hour, which enhances the adhesion of the photoresist on the sample surface.

Figure (a) : Laser interference Lithography

Figure (b) : Optical layout of the laser-interference lithography setup with attenuators A and mirrors M.

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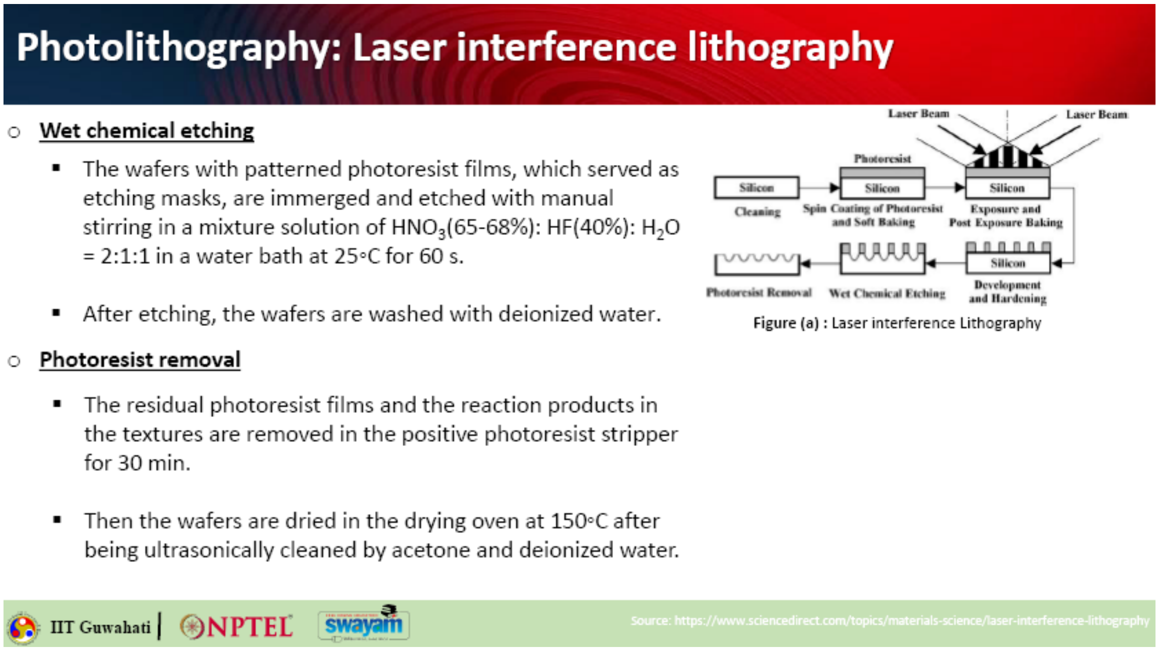
Source: https://www.sciencedirect.com/topics/materials-science/laser-interference-lithography

So in this case what happens a nano group pattern can be recorded on the photo resist and after the exposure is done the silicon wafers are again baked in a drying oven at 100 degree centigrade for 10 minutes duration and that actually eliminate the standing wave effect in the photoresist film. So once it is done you go to the next step which is development and hardening. The photoresist films are immersed into positive photoresist developer for 15 second to remove the exposed parts and they also form the photoresist patterns in water bath at 25 degree centigrade and then it is rinsed with deionized water repeatedly. So this is how you do the development of the patterns and afterwards you again want to harden it so the samples are basically baked in the drying oven at 120 degree centigrade for an hour and this enhances the adhesion of the photoresist on the sample surface. So, you can see with this you are actually able to have this particular patterns here so this and after developing you are just left with this particular photoresist pattern and this is also now hardened.



Photolithography: Laser interference lithography

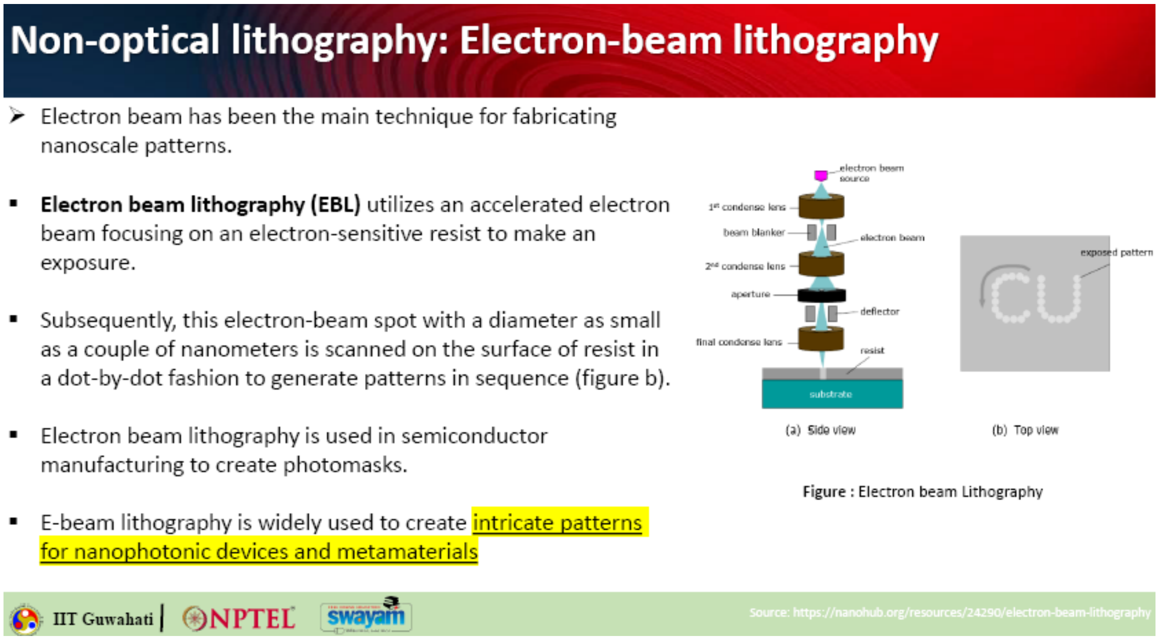
- **Wet chemical etching**
  - The wafers with patterned photoresist films, which served as etching masks, are immerged and etched with manual stirring in a mixture solution of HNO_3(65-68%): HF(40%): H_2O = 2:1:1 in a water bath at 25◦C for 60 s.
  - After etching, the wafers are washed with deionized water.
- **Photoresist removal**
  - The residual photoresist films and the reaction products in the textures are removed in the positive photoresist stripper for 30 min.
  - Then the wafers are dried in the drying oven at 150◦C after being ultrasonically cleaned by acetone and deionized water.

Figure (a) : Laser interference Lithography

Source: https://www.sciencedirect.com/topics/materials-science/laser-interference-lithography

Then you go to the fifth step which is wet chemical etching so we will study about etching subsequently. So what happens here the wafers with pattern so this is the silicon wafer with the pattern photoresist film on top so it actually works like a etching mask. So the portions which are not portions of silicon which are not exposed to the etchant will not get etched but the portions which are open they will get etched as simple as that so these openings the gaps they will get etched out. So what are the typical etchant so they are immersed this kind of thing is immersed and etched with manual stirring of a mixture solution of nitric acid with so this is the percentage 65 to 68 percent of nitric acid and hydrogen fluoride and then water this is the ratio in a water bath at 25 degree centigrade and this is the time around 60 seconds you do it and after etching the wafer is basically washed with deionized water and you will get this kind of a structure. And finally you have to get rid of this photoresist so the residual photoresist films that you have seen in the wet etching phase needs to be removed but that can be done in this particular stage so you see what happens the reaction products in the textures are removed in positive photoresist stripper so this is another solvent that can dissolve your photoresist that you have used and typically it takes around 30 minutes time.

And then finally you have got this one you have got a patterned silicon wafer and this wafer are then dried in the drying oven and the temperature is set to be around 150 degree centigrade okay and this is done after they are ultrasonically cleaned by acetone and deionized water. So this is how you get the final patterned substrate so this is very useful for as I mentioned for photonic crystal structures okay and also for metamaterials so this is very very useful in our case. Now let us look into the other type of lithography which is non-optical lithography the first thing that will come to your mind will be instead of using photons can we use electron beam okay so that technique is called electron beam lithography. So electron beam has been the main technique for fabricating nanoscale patterns okay so electron beam lithography utilizes an accelerated electron beam focusing on an electron sensitive resist so in the previous case you used photoresist which are basically sensitive to the UV light that is falling here you have to look for a resist that is sensitive to electrons and that will help you to make the exposure okay. So you can see this is the pattern typical photo electron lithography setup so you have got an electron beam source you have the first condense lens and you have a beam blanker so you can electron beam you have the second lens you have got the aperture deflector final lens and then it focuses and does the patterning okay.



Non-optical lithography: Electron-beam lithography

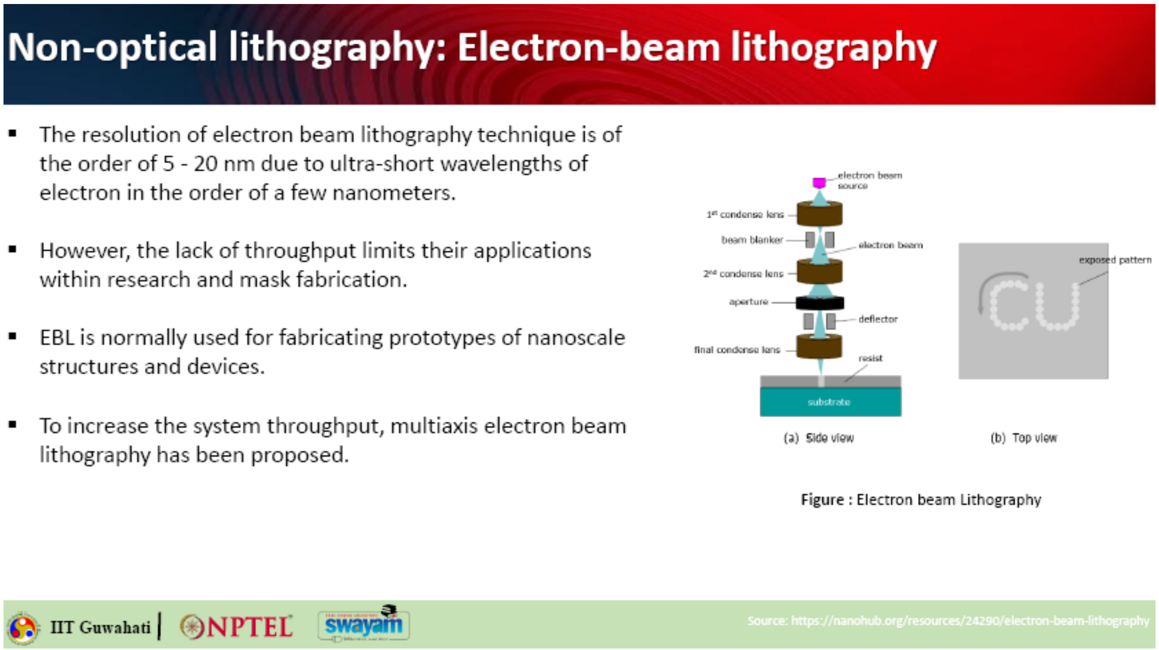
- Electron beam has been the main technique for fabricating nanoscale patterns.
- **Electron beam lithography (EBL)** utilizes an accelerated electron beam focusing on an electron-sensitive resist to make an exposure.
- Subsequently, this electron-beam spot with a diameter as small as a couple of nanometers is scanned on the surface of resist in a dot-by-dot fashion to generate patterns in sequence (figure b).
- Electron beam lithography is used in semiconductor manufacturing to create photomasks.
- E-beam lithography is widely used to create intricate patterns for nanophotonic devices and metamaterials

(a) Side view (b) Top view

Figure : Electron beam Lithography

Source: https://nanohub.org/resources/24290/electron-beam-lithography

So you can see here on this particular diagram how the patterns are created so these are basically in the shape of electron beam spot with a diameter that can be as small as couple of nanometers and it is scanned through the surface of the resist in a dot by dot fashion okay like this and then you can generate the structure that you want to make. So you can actually see this is the overall pattern but every dot is now in one stage you are just getting one dot so this is a very very fine resolution you can understand. So even lithography is used in semiconductor manufacturing to create the photo masks okay and they are also very very widely used for making any kind of intricate patterns for nanophotonic devices and metamaterials. So again this technique e-beam lithography becomes a very very commonly used technique in our domain. So here the resolution is of great importance as you can see the resolution of e-beam lithography is of the order of 5 to 20 nanometer okay due to the ultra short wavelength of electron which is in the order of few nanometers.



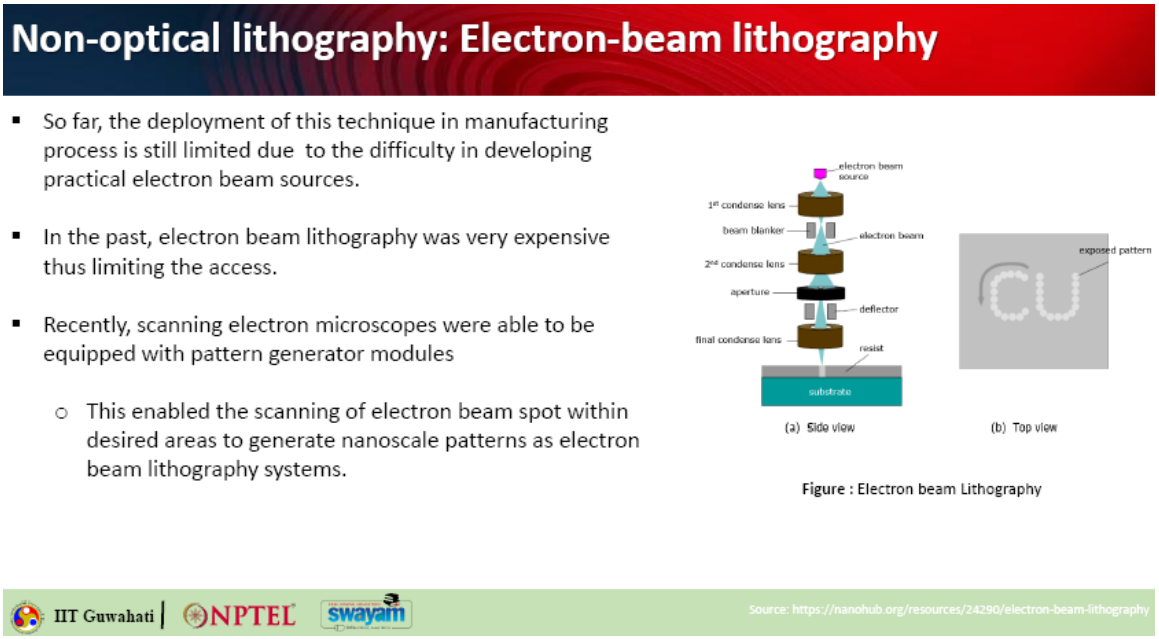
Non-optical lithography: Electron-beam lithography

- The resolution of electron beam lithography technique is of the order of 5 - 20 nm due to ultra-short wavelengths of electron in the order of a few nanometers.
- However, the lack of throughput limits their applications within research and mask fabrication.
- EBL is normally used for fabricating prototypes of nanoscale structures and devices.
- To increase the system throughput, multiaxis electron beam lithography has been proposed.

Figure : Electron beam Lithography

Source: https://nanohub.org/resources/24290/electron-beam-lithography

However the lack of throughput limits their applications within research and mask fabrication. So you do not actually see large scale fabrication using e-beam lithography and e-beam lithography is normally used for fabricating prototypes of nanoscale structures and devices and every research institutions a good research institutions in the world they have e-beam lithography setup where researchers can fabricate this kind of nanoscale devices and test their prototypes. So, to increase the system throughput multi-axis electron beam lithography has been proposed but once only the throughput will increase okay then only it can go to the mass fabrication you know large fabrication skills.



Non-optical lithography: Electron-beam lithography

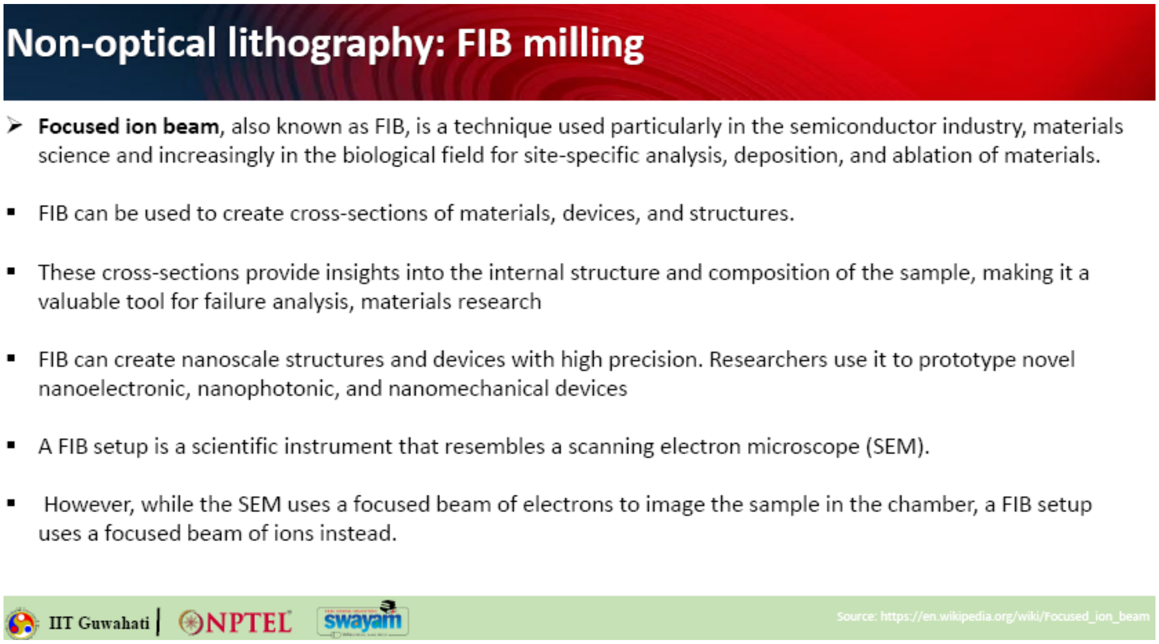
- So far, the deployment of this technique in manufacturing process is still limited due to the difficulty in developing practical electron beam sources.
- In the past, electron beam lithography was very expensive thus limiting the access.
- Recently, scanning electron microscopes were able to be equipped with pattern generator modules
  - This enabled the scanning of electron beam spot within desired areas to generate nanoscale patterns as electron beam lithography systems.

Figure : Electron beam Lithography

Source: https://nanohub.org/resources/24290/electron-beam-lithography

So far the development of the technique in the manufacturing process is still limited as I mentioned it is due to the difficulty in developing practical electron beam sources. So this source getting the source is not that easy and in the past electron beam lithography was very expensive and thus it was limiting the access but recently with the development of scanning electron microscopes okay this microscopes were able to be equipped with some pattern generator modules and this enabled the scanning of electron beam spot within the desired areas to generate nanoscale patterns as e-beam lithography system.

So that has actually helped the electron beam lithography to a great extent. Another non-optical lithography technique is FIB that is focused ion beam lithography. This is a technique which is used particularly in semiconductor industry, material science and they are also getting increasingly popular in biological fields for doing site specific analysis deposition or ablation of materials. So focused ion beams can be used to create cross sections of materials, devices and structures. These cross sections can provide insight into the internal structure and composition of a sample making this FIB milling a very valuable tool for failure analysis and material research. FIB can also create nanoscale structures and devices with high precision and researchers use it to prototype novel nanoelectronic, nanophotonic and nanomechanical devices.



Non-optical lithography: FIB milling

- **Focused ion beam**, also known as FIB, is a technique used particularly in the semiconductor industry, materials science and increasingly in the biological field for site-specific analysis, deposition, and ablation of materials.
- FIB can be used to create cross-sections of materials, devices, and structures.
- These cross-sections provide insights into the internal structure and composition of the sample, making it a valuable tool for failure analysis, materials research
- FIB can create nanoscale structures and devices with high precision. Researchers use it to prototype novel nanoelectronic, nanophotonic, and nanomechanical devices
- A FIB setup is a scientific instrument that resembles a scanning electron microscope (SEM).
- However, while the SEM uses a focused beam of electrons to image the sample in the chamber, a FIB setup uses a focused beam of ions instead.

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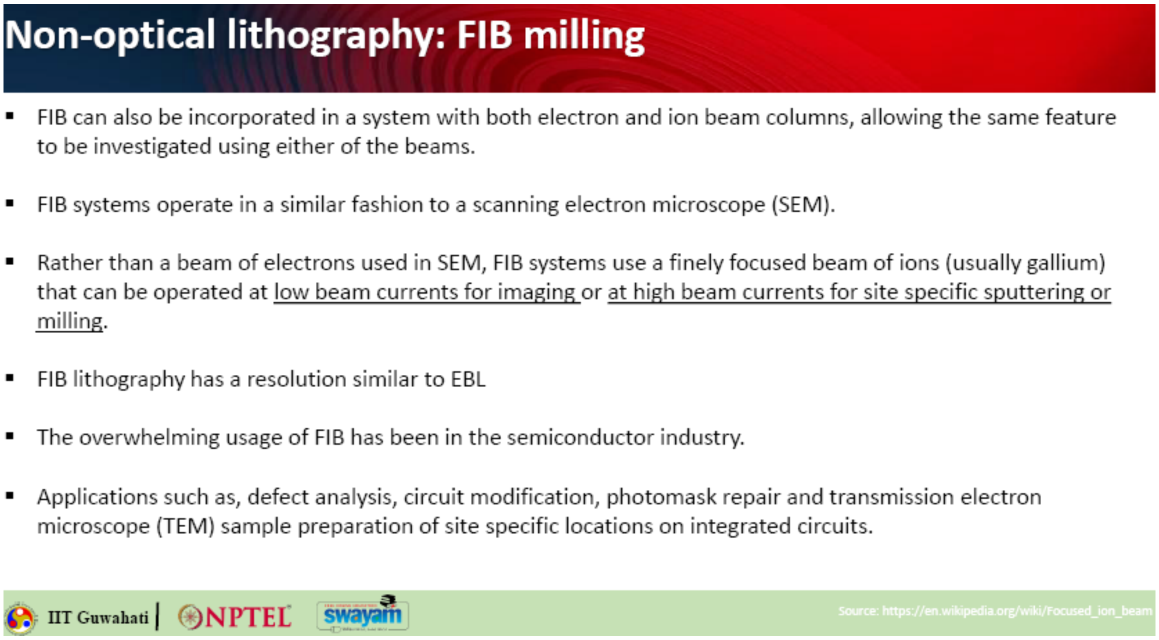
Source: https://en.wikipedia.org/wiki/Focused_ion_beam

So the setup of an FIB resembles that of scanning electron microscope. However, while SEM uses a focused beam of electrons to image the sample in a container in a chamber, FIB setup uses focused beams of ions. It is not of electrons, it is of ions. So that is the main difference between FIB and SEM. So FIB can be incorporated in a system with both electrons and ion beam columns allowing the same feature to be investigated by using either of the beams. So you can use either electron beam or ion beam and you can have this dual functionality and this is possible because the FIB system works in a similar fashion to a scanning electron microscope.

Just that the difference is rather than using electrons in SEM, FIB using a finely focused beam of ions typically it is the gallium ion and that can be operated at low beam current which is useful for imaging or you can use at high beam current for site specific sputtering or milling. If you want to mill some particular material nanomaterial, okay, a microscope material you can use this high beam currents in FIB for doing it, okay. So the resolution in FIB is very similar to e-beam lithography and you can see an overwhelming use of FIB in the semiconductor industry. So what are the typical applications you can think of? It can be used for defect analysis, circuit modification, photo mask repair, transmission electron microscope, sample preparation of site specific locations on ICs.



Non-optical lithography: FIB milling

- FIB can also be incorporated in a system with both electron and ion beam columns, allowing the same feature to be investigated using either of the beams.
- FIB systems operate in a similar fashion to a scanning electron microscope (SEM).
- Rather than a beam of electrons used in SEM, FIB systems use a finely focused beam of ions (usually gallium) that can be operated at low beam currents for imaging or at high beam currents for site specific sputtering or milling.
- FIB lithography has a resolution similar to EBL
- The overwhelming usage of FIB has been in the semiconductor industry.
- Applications such as, defect analysis, circuit modification, photomask repair and transmission electron microscope (TEM) sample preparation of site specific locations on integrated circuits.

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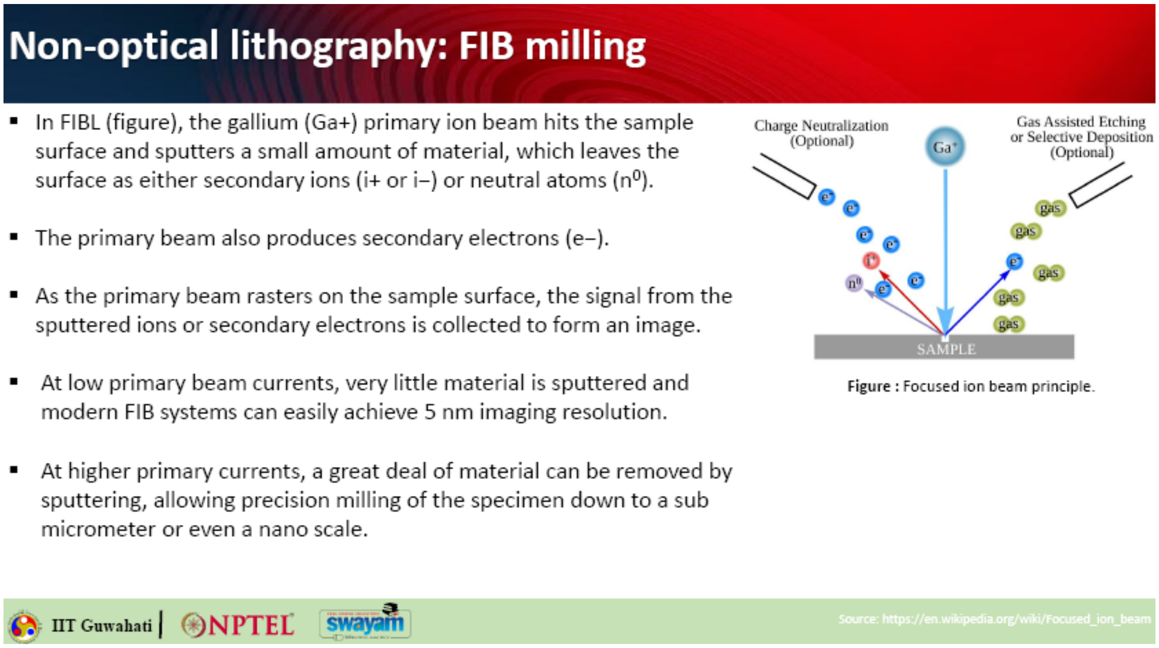
Source: https://en.wikipedia.org/wiki/Focused_ion_beam

So all these integrate applications can be done using FIB. So this is how the process looks like. So here in FIBL, focused ion beam lithography, the gallium ion which is basically the primary ion beam that hits the sample, okay, surface and sputters small amount of molecule material, okay, and you can see these materials leave this surface either in the form of secondary ions like they can be positive ions or negative ions or neutral atoms, okay, and they can also produce secondary electrons like this, okay. So as the primary beam rasters on the or you can say scans on the sample surface, the signal from the sputtered ion or the secondary electrons are basically collected to form a particular image, okay. So as I mentioned at low primary beam current, very little material will get sputtered, okay, and you can achieve up to like 5 nanometer imaging resolution in the modern FIB system using this particular technique. However, if you want to do some milling, okay, you have to operate at higher primary currents.

In that case, a great deal of material can be removed by sputtering which allows precision milling of the specimen down to, sub-micrometer or even to nanoscale. So this is how, FIB milling is very, very popular. Last but not the least, a very important method in lithography is the nanoimprint lithography, okay. So, nanoimprint lithography is also a cutting edge technique.



Non-optical lithography: FIB milling

- In FIBL (figure), the gallium (Ga+) primary ion beam hits the sample surface and sputters a small amount of material, which leaves the surface as either secondary ions (i+ or i–) or neutral atoms (n^0).
- The primary beam also produces secondary electrons (e–).
- As the primary beam rasters on the sample surface, the signal from the sputtered ions or secondary electrons is collected to form an image.
- At low primary beam currents, very little material is sputtered and modern FIB systems can easily achieve 5 nm imaging resolution.
- At higher primary currents, a great deal of material can be removed by sputtering, allowing precision milling of the specimen down to a sub micrometer or even a nano scale.

Figure : Focused ion beam principle.

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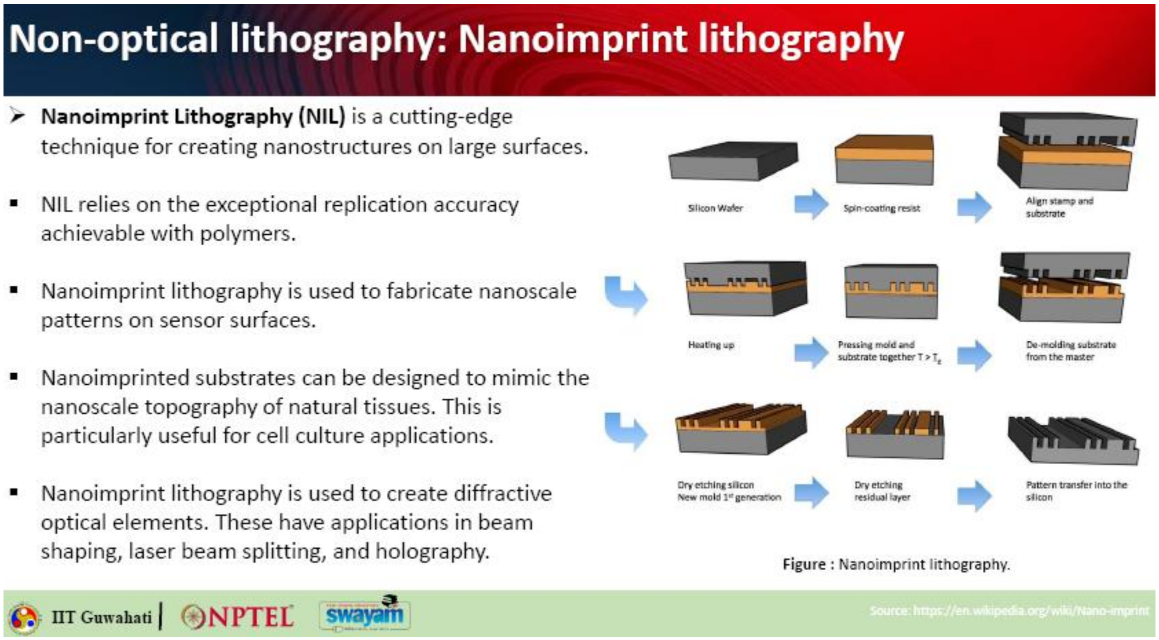
Source: https://en.wikipedia.org/wiki/Focused_ion_beam

It allows creating nanostructures on large surfaces. So this is how it works. You can take a silicon wafer and coat it with, spin coat it with some resist and then you align a stamp to this particular substrate and then you heat up, okay, you press the mold and the substrate together at that hot temperature, okay, and then you demold the substrate from the master, so you remove it. Then you do dry etching and that gives you new mold first generation. This is the dry etching of the residual layer and then the final etching will transfer the material, okay, you will get the pattern that is transferred onto the, so on this when you do dry etching you finally get this particular pattern transferred onto the silicon. So, as you can see here, this particular lithography relies on the exceptional replication accuracy which is achievable with the polymers.



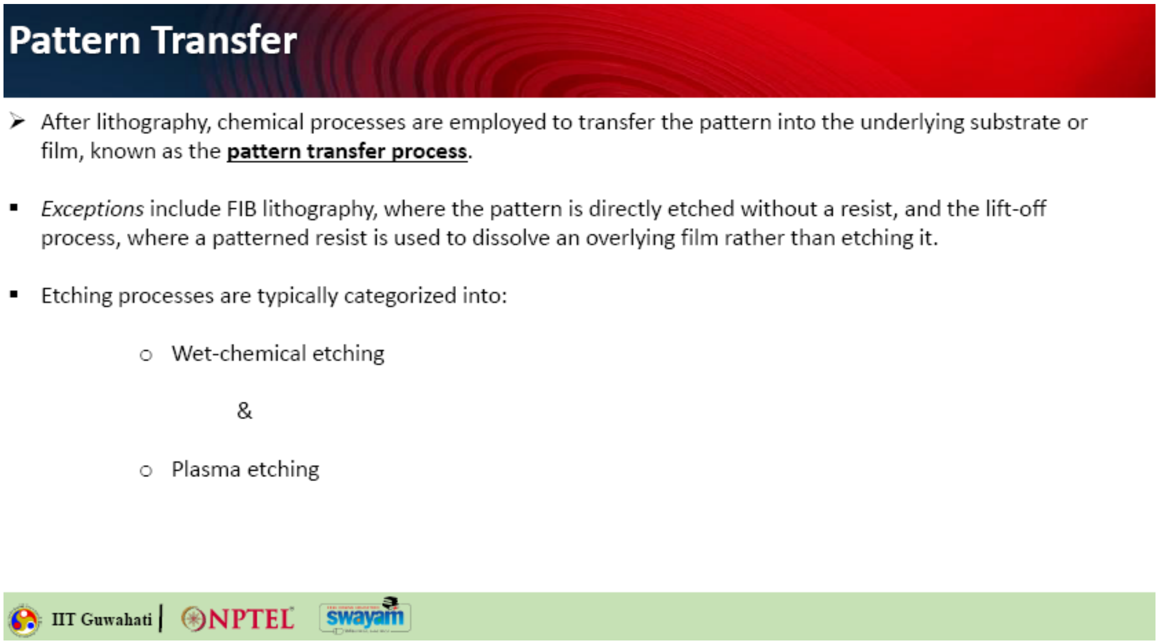
Non-optical lithography: Nanoimprint lithography

- **Nanoimprint Lithography (NIL)** is a cutting-edge technique for creating nanostructures on large surfaces.
  - NIL relies on the exceptional replication accuracy achievable with polymers.
  - Nanoimprint lithography is used to fabricate nanoscale patterns on sensor surfaces.
  - Nanoimprinted substrates can be designed to mimic the nanoscale topography of natural tissues. This is particularly useful for cell culture applications.
  - Nanoimprint lithography is used to create diffractive optical elements. These have applications in beam shaping, laser beam splitting, and holography.

Figure : Nanoimprint lithography.

Source: https://en.wikipedia.org/wiki/Nano-imprint

So, nanoimprint lithography is used to fabricate nanoscale patterns on sensor surfaces. So you can actually make this kind of patterns and nanoimprinted substrates can be designed to mimic the nanoscale topology of natural tissues. So you can actually go for any kind of complicated design, okay, and this will be very very useful for cell culture applications. Nanoimprint lithography is used to create diffractive elements and this have applications in beam shaping, laser beam splitting and also in holography, okay. So that brings us to the discussion of different lithography techniques.



Pattern Transfer

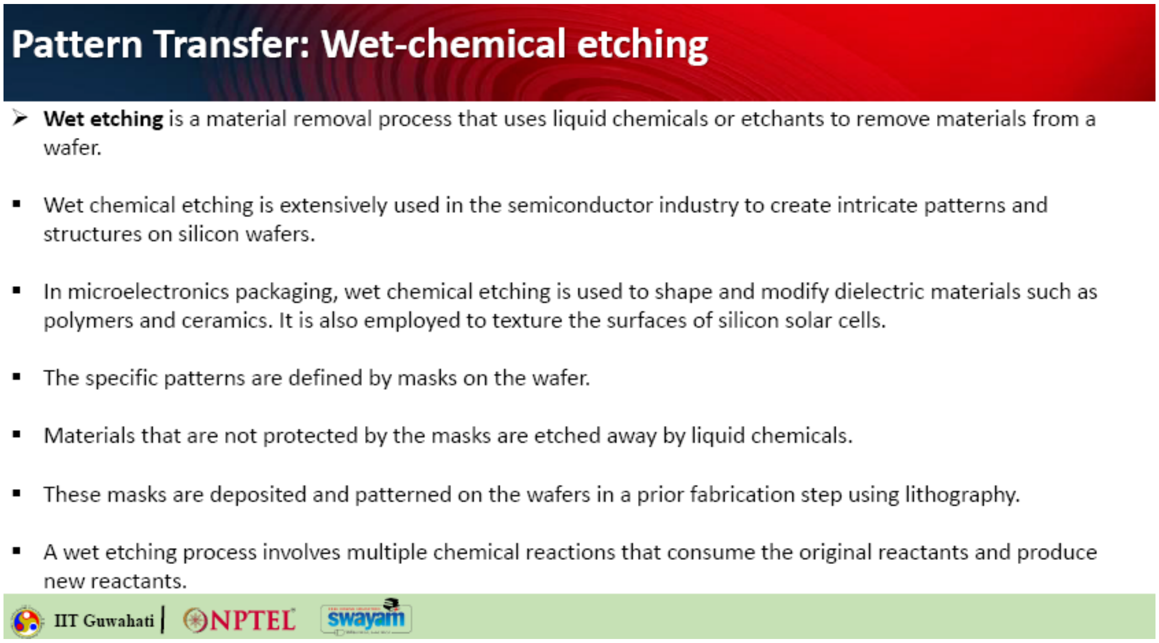
- After lithography, chemical processes are employed to transfer the pattern into the underlying substrate or film, known as the **pattern transfer process**.
  - *Exceptions* include FIB lithography, where the pattern is directly etched without a resist, and the lift-off process, where a patterned resist is used to dissolve an overlying film rather than etching it.
  - Etching processes are typically categorized into:
    - Wet-chemical etching

      &

    - Plasma etching

Now quickly let us look into the pattern transfer methods, okay. So after lithography we have seen that the chemical processes get involved to transfer the pattern into the underlying substrate or the film and this process is called pattern transfer process. And there is an exception in FIB lithography where the pattern is directly etched without a resist and the lift-up process where the pattern resist is used to dissolve an overlying film rather than etching it. But in other cases you are actually doing this etching process and this etching process can be categorized typically into wet chemical etching and plasma etching techniques. So let us look into the wet chemical etching or wet etching first. So wet etching is basically a material removal process that uses liquid chemicals or etchants to remove a material from a wafer.

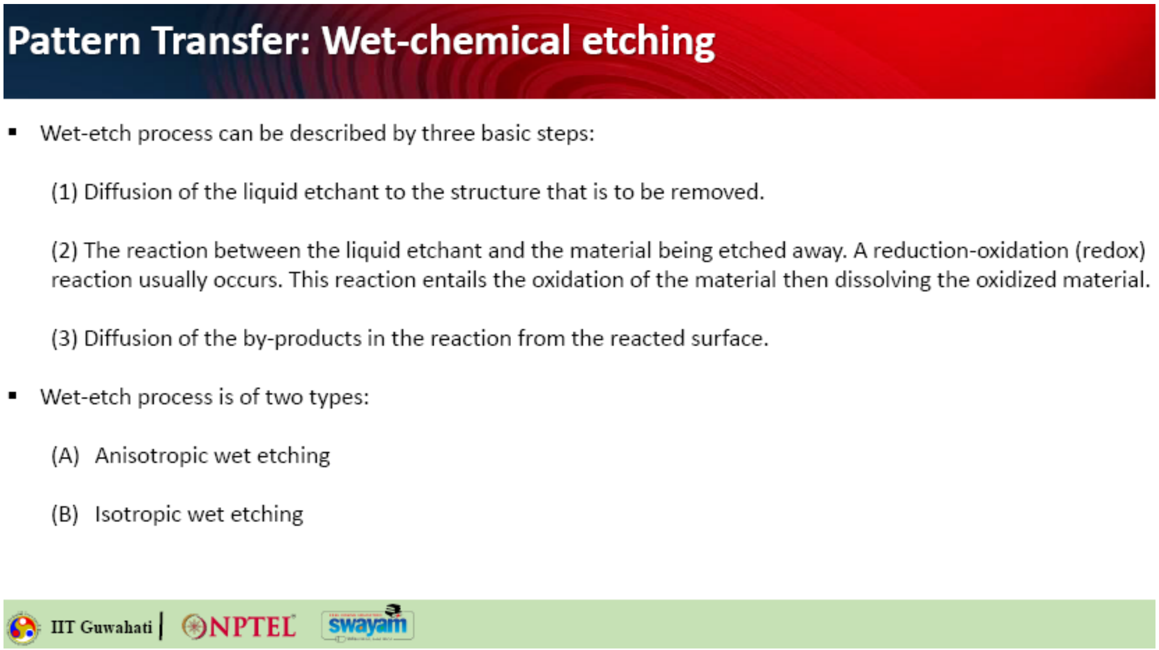
So this kind of etching is extensively used in the semiconductor industry that allows you to create intricate patterns and structures on silicon wafers. So obviously the same method can also be used for our optical devices and photonic metamaterials. In microelectronics packaging wet chemical etching is used to shape and modify the dielectric materials such as polymers and ceramics and it is also employed to structure the surface of silicon solar cells. The specific patterns are defined by masks on the wafer.



Pattern Transfer: Wet-chemical etching

- **Wet etching** is a material removal process that uses liquid chemicals or etchants to remove materials from a wafer.
- Wet chemical etching is extensively used in the semiconductor industry to create intricate patterns and structures on silicon wafers.
- In microelectronics packaging, wet chemical etching is used to shape and modify dielectric materials such as polymers and ceramics. It is also employed to texture the surfaces of silicon solar cells.
- The specific patterns are defined by masks on the wafer.
- Materials that are not protected by the masks are etched away by liquid chemicals.
- These masks are deposited and patterned on the wafers in a prior fabrication step using lithography.
- A wet etching process involves multiple chemical reactions that consume the original reactants and produce new reactants.

So that will tell you about what is the pattern that is going to be etched out. So materials which are not protected by the masks are actually etched out by the liquid chemicals and which are protected they are fine. And these masks are deposited and patterned on the wafers prior to the fabrication step which is done using lithography that you have just seen. A wet chemical etching process involves multiple chemical reactions that consume the original reactants and produce new reactants. So this wet etching process can be described in three steps. First you have diffusion of the liquid etchant to the surface that has to be removed and then there is a reaction between the liquid etchant and the material that is getting etched away.



Pattern Transfer: Wet-chemical etching

- Wet-etch process can be described by three basic steps:

  (1) Diffusion of the liquid etchant to the structure that is to be removed.

  (2) The reaction between the liquid etchant and the material being etched away. A reduction-oxidation (redox) reaction usually occurs. This reaction entails the oxidation of the material then dissolving the oxidized material.

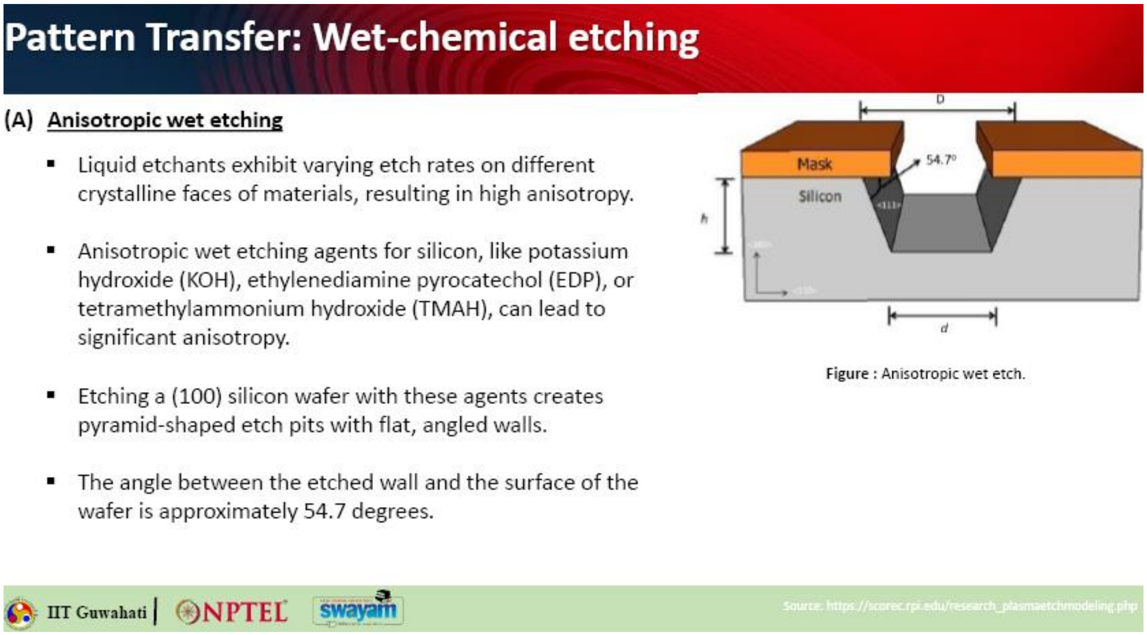
  (3) Diffusion of the by-products in the reaction from the reacted surface.

- Wet-etch process is of two types:

  (A) Anisotropic wet etching

  (B) Isotropic wet etching

A reduction oxidation or you can say redox kind of reaction usually takes place and this reaction entails the oxidation of the material then dissolving the oxidized materials. And finally you have diffusion of the byproducts in the reaction from the reacted surface. So, this is how the wet etching process happens and there are two types of wet etching one is anisotropic the other one is isotropic.



Pattern Transfer: Wet-chemical etching

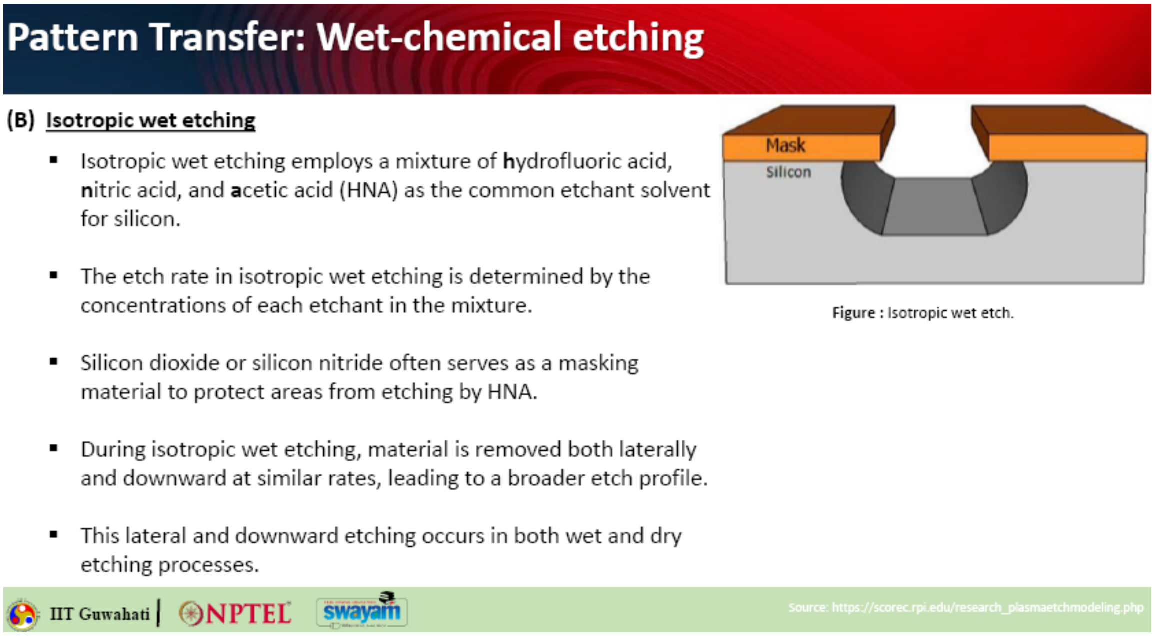
(A) **Anisotropic wet etching**

- Liquid etchants exhibit varying etch rates on different crystalline faces of materials, resulting in high anisotropy.
- Anisotropic wet etching agents for silicon, like potassium hydroxide (KOH), ethylenediamine pyrocatechol (EDP), or tetramethylammonium hydroxide (TMAH), can lead to significant anisotropy.
- Etching a (100) silicon wafer with these agents creates pyramid-shaped etch pits with flat, angled walls.
- The angle between the etched wall and the surface of the wafer is approximately 54.7 degrees.

Figure : Anisotropic wet etch.

Source: https://scorec.rpi.edu/research_plasmaetchmodeling.php

So as the name suggests this is how anisotropic wet etching typically looks like. So here the liquid etchant exhibits varying etching rate on different crystalline phases of the materials and that gives you high anisotropic. So anisotropic wet etching agents for silicon will be something like potassium hydroxide than EDP or TMAH and they can actually lead to significant anisotropy in the etched surface.



Pattern Transfer: Wet-chemical etching

(B) Isotropic wet etching

- Isotropic wet etching employs a mixture of **h**ydrofluoric acid, **n**itric acid, and **a**cetic acid (HNA) as the common etchant solvent for silicon.
- The etch rate in isotropic wet etching is determined by the concentrations of each etchant in the mixture.
- Silicon dioxide or silicon nitride often serves as a masking material to protect areas from etching by HNA.
- During isotropic wet etching, material is removed both laterally and downward at similar rates, leading to a broader etch profile.
- This lateral and downward etching occurs in both wet and dry etching processes.

Figure : Isotropic wet etch.

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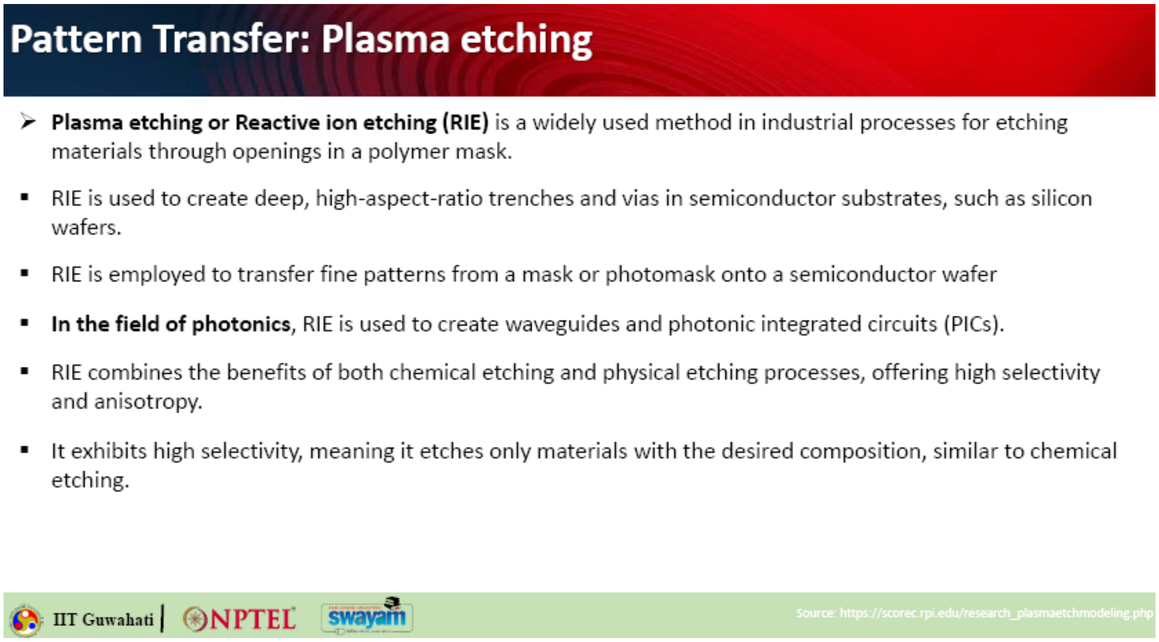
Source: https://scorec.rpi.edu/research_plasmaetchmodeling.php

So, as you can see this is the angle between the etched wall and the surface of the wafer. But when you go for isotropic wet etching it happens in equally in all direction as isotropic the word means. So here you can see that you are planning to etch a 100 silicon wafer with this kind of etching agents and they create one in a pyramid shaped etch pits which have got flat and angled walls and typically this angle is around 54.7 degree.



Pattern Transfer: Plasma etching

- **Plasma etching or Reactive ion etching (RIE)** is a widely used method in industrial processes for etching materials through openings in a polymer mask.
- RIE is used to create deep, high-aspect-ratio trenches and vias in semiconductor substrates, such as silicon wafers.
- RIE is employed to transfer fine patterns from a mask or photomask onto a semiconductor wafer
- **In the field of photonics**, RIE is used to create waveguides and photonic integrated circuits (PICs).
- RIE combines the benefits of both chemical etching and physical etching processes, offering high selectivity and anisotropy.
- It exhibits high selectivity, meaning it etches only materials with the desired composition, similar to chemical etching.

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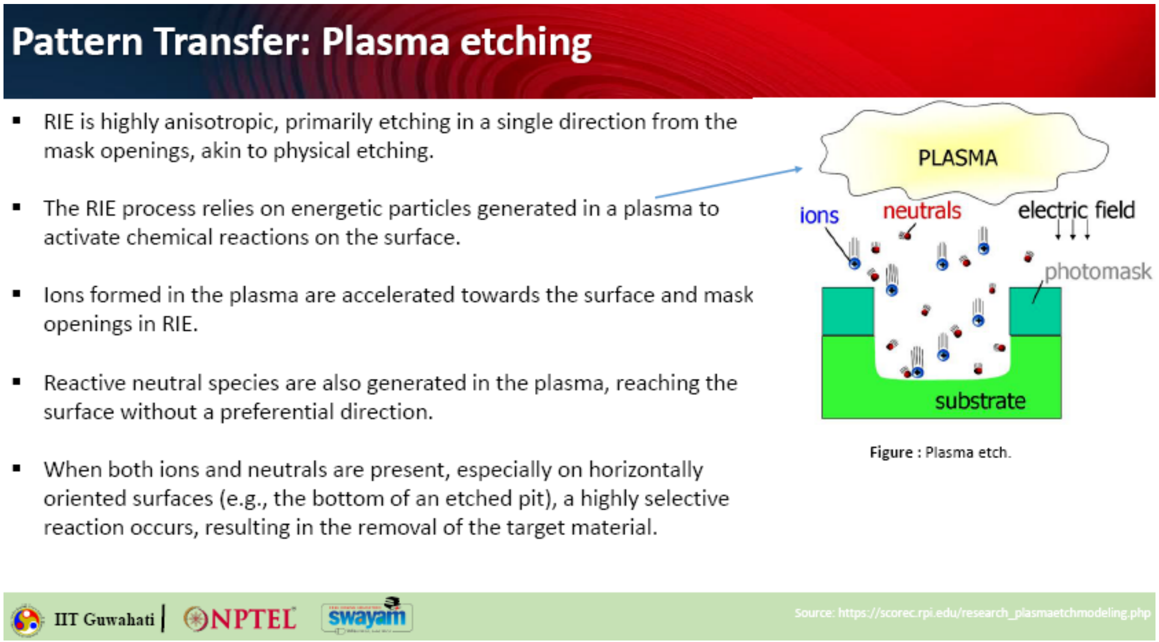
Source: https://scorec.rpi.edu/research_plasmaetchmodeling.php

So isotropic wet etching employs a mixture of hydrofluoric acid nitric acid and acetic acid in short you can call them HNA and that is used as the common etchant solvent for silicon and the etch rate in isotropic wet etching is determined by the concentration of the etchant in the mixture. So silicon dioxide or silicon nitride often serves as the masking material that you see here that can be used to protect the areas from etching by HNA and during this isotropic wet etching the material is removed both laterally and downward at the same rate. So that will actually give you a broader etch profile. So laterally in XY direction and Z direction the etching happens in same rate.

So that is why it is called isotropic etching. So this lateral and downward etching occurs in both wet and dry etching processes. And the last method of this etching will be plasma etching. Now plasma etching are also popularly known as reactive ion etching or RIE is a very widely used method for industrial processes for etching materials through opening in polymer masks. So RIE or reactive ion etching is used to create deep high aspect ratio trenches. So, where it is very thin but very deep those kind of things you can use plasma etching and you can create via the connectors in semiconductor substrate such as silicon wafers.



Pattern Transfer: Plasma etching

- RIE is highly anisotropic, primarily etching in a single direction from the mask openings, akin to physical etching.
- The RIE process relies on energetic particles generated in a plasma to activate chemical reactions on the surface.
- Ions formed in the plasma are accelerated towards the surface and mask openings in RIE.
- Reactive neutral species are also generated in the plasma, reaching the surface without a preferential direction.
- When both ions and neutrals are present, especially on horizontally oriented surfaces (e.g., the bottom of an etched pit), a highly selective reaction occurs, resulting in the removal of the target material.

Figure : Plasma etch.

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Source: https://scorec.rpi.edu/research_plasmaetchmodeling.php

So reactive ion etching is very very popularly used in semiconductor IC industry and they are also used to transfer fine patterns from a mask or photo mask onto a semiconductor wafer. So in the field of photonics reactive ion etching can help us create the wave guides and photonic indicator circuit. So it is very important process that we should pay attention to. So this method combines the benefit coming from both chemical etching and physical etching processes and it offers high selectivity as well as anisotropy. And this high selectivity means it etches only materials with desired composition just like the chemical etching.

So let us look into this process here. So reactive ion etching as I mentioned is highly anisotropic and it primarily etches in a single direction from the mask opening just like the physical etching. And the reactive ion process relies on energetic particles generated in a plasma to activate the chemical reaction on the surface. So this is the plasma and you can see the ions formed in the plasma are accelerated towards the surface and mask openings in the so this is the photo mask and this is the substrate this will be the opening. So this is how the ions are basically allowed to enter and the reactive neutral species are also generated in the plasma reaching the surface without a preferential dimension. So when both the ions and neutrals are present especially on horizontally oriented surfaces for example the bottom of an etched pit a highly selective reaction occurs and that actually gives you the removal of the target material.

So as you understand plasma etching or reactive ion etching is very very important in situations where you want to have very deep high aspect ratio trenches and these are very important for some intricate nanophotonic or nanoelectronic structures. So that more or less covers all the topics related to lithography and pattern transfer. As you understand these topics in themselves are like very detailed so we may go into the details of each and every topic but this is not objective of this course this course is just telling you the different topics or techniques which are available in the industry and you can study about them when you want to actually fabricate your device in the future. So with that we will stop here thank you for your attention and we will discuss about nanophotonic characterization methods in the next lecture and that will also be the final lecture for this course and thank you if you have got any queries you can always drop an email to me mentioning MOOC in the subject line.