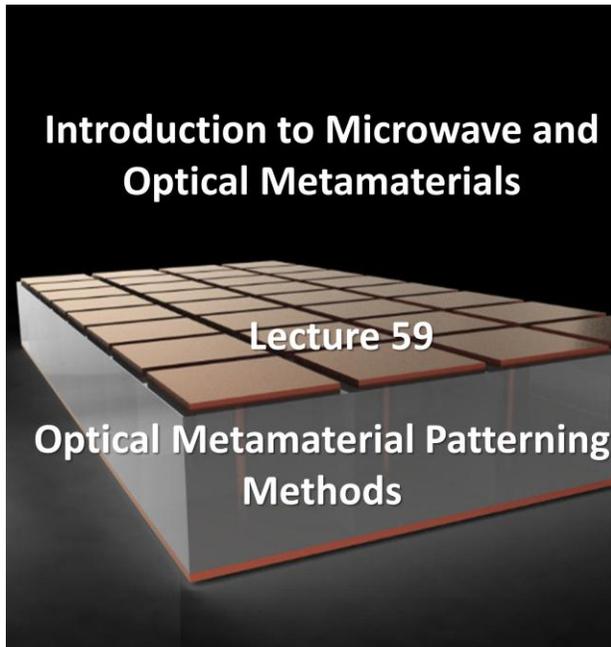


Course Name: Introduction to Microwave and Optical Metamaterials
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Week-12
Lecture-59

Lec 59: Optical Metamaterial Patterning Methods



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Hello everyone, welcome to Lecture 59 of the online course on Introduction to Microwave and Optical Metamaterials. Today's lecture will be on optical metamaterial patterning methods.

Lecture Outline

- **Patterning Methods for Optical Metamaterials**
 - **Photolithography**
 - ✓ Deep UV Lithography
 - ✓ Extreme UV Lithography
 - ✓ Laser Interference Lithography
 - **Non-optical Lithography techniques**
 - ✓ Electron-beam Lithography
 - ✓ FIB Milling
 - ✓ Nanoimprint Lithography



So here is the lecture outline. We will look into different patterning methods for making optical metamaterials. First, we will discuss about different photolithography methods like deep UV lithography, extreme UV lithography, and laser interference lithography. And then we will also discuss some non-optical lithography methods like electron beam lithography, FIB is focused ion beam milling and nano-imprint lithography.

Photolithography: Deep UV and Extreme UV Lithography

- Deep UV (DUV) and Extreme UV (EUV) Lithography: Advanced forms of photolithography that use very short wavelengths of light to pattern extremely small features.
 - They are the workhorses of the semiconductor industry for creating integrated circuits with features at the nanometer scale.
- Deep UV (DUV): Uses a UV laser (typically a 193 nm argon fluoride laser) to pattern features down to about 20-40 nanometers.
 - While not as high-resolution as EUV, it's a mature, high-throughput technology that is still used to produce a wide range of devices, including many optical metamaterials.
- Extreme UV (EUV): Represents the next step in resolution, using a much shorter wavelength of light, around 13.5 nm.
 - This allows for the fabrication of features smaller than 10 nanometers, essential for the most advanced optical metamaterials and the densest modern microchips.
 - EUV systems are extremely complex and expensive, requiring a vacuum environment and reflective optics because almost all materials absorb EUV light.



Source: <https://www.newport.com/n/deep-uv-photolithography>

So, let us first discuss lithography. So, since projection lithography, which was discussed

earlier, is only useful for small die preparation, which is also known as the stepper system. Here we will look into deep ultraviolet and extreme ultraviolet, which are deep UV and extreme UV lithography. Which are basically advanced forms of photolithography that use very, very short wavelengths of light that enable you to pattern extremely small features. Now, these are the workhorses of the semiconductor industry that helps you create the integrated circuits where the feature size is typically in the nanometer scale. Deep UV basically the name also suggests that it basically uses the UV laser which is typically 193 nanometer argon fluoride laser is used, okay. So that is used to pattern the features down to about 20 to 40 nanometers. So, as you can see, while the resolution is not as high as the extreme ultraviolet that you will be seeing next.

But this deep UV is a mature technology. So, you can expect high throughput, and it will still be used to produce a wide range of devices, including many optical metamaterials. Now, when you go one more step ahead for higher resolution, you can think of extreme UV that is basically the next step in resolution because it uses a much shorter wavelength of light around 13.5 nanometers. So, you can see that it will basically allow the fabrication of features that are smaller than 10 nanometers, okay.

This allows for the fabrication of features that are smaller than 10 nanometers and these are essential for the most advanced optical metamaterials and densest modern microchips. So, extreme UV systems are extremely complex and expensive. and they require vacuum environment and reflective optics ok, because almost every material kind of absorb this extreme UV light ok.

So, now let us go into the details of deep-UV lithography.

Photolithography: Deep UV (DUV) Lithography

➤ DUV Photolithography (193 nm, Projection Optics): Step-and-scan system

- This technology of photolithography is based on projection optics (not contact printing):
 - Since the pattern on the photomask is much larger than the final pattern developed on the photoresist.
- The optical system in a 193 nm photolithography tool is known as a **catadioptric system**.
- The DUV photolithography process uses a catadioptric system to project patterns onto a wafer.
- Optical **catadioptric system** → combines **lenses (refractive) + mirrors (reflective)**; to direct and condition light from a 193 nm laser.
- **Catadioptric System**: This system limits chromatic aberration while accommodating a broad bandwidth of laser light.
- The refractive elements are made of synthetic fused silica or calcium fluoride because these materials have low absorption of 193 nm light.

So, a couple of important things that we are going to discuss about deep UV lithography that uses a 193-nanometer wavelength and the standard technique is step and scan system and they also use projection optics ok.

So, this is a technology of photolithography that is basically based on projection optics, which means it is not a contact-based method, right? So, here you will see that since the pattern that you make on the photo mask is much larger than the final pattern that will be developed on the photoresist, right. So, the optical system in this kind of 193-nanometer photolithography tool is also known as a catadioptric system. So, the deep UV photolithography process basically uses a catadioptric system to project patterns onto a wafer. So, how does it work? So, you have this optical catadioptric system that basically combines lenses which are refractive systems and mirrors that are reflective systems, okay. So, this combination is basically designed to direct and condition light from a 193-nanometer laser.

Now, this particular catadioptric system basically limits chromatic aberration while accommodating a broad bandwidth of laser light. So, the refractive elements like the lens and all these things that you use are basically made of synthetic fused silica or calcium fluoride because these materials have very low absorption in this particular wavelength 193 nanometer.

Photolithography: Deep UV (DUV) Lithography

➤ DUV Photolithography (193 nm, Projection Optics): Step-and-scan system

- **Photomasks (Reticles):** These are made of fused silica with chrome patterns.
- **Exposure Mechanism:**
 - It uses step-and-scan process:
 - A slit of light scans across the reticle (mask).
 - Pattern is projected onto a photoresist-coated wafer at reduced feature size (due to reduction lens).
 - Both reticle and wafer move simultaneously & precisely to replicate the full die pattern.
 - After one die is patterned, system “steps” to the next die area.
- **Immersion Lithography:**
 - Thin layer of water maintained between wafer and objective lens.
 - Increases resolution and allows finer feature patterning.

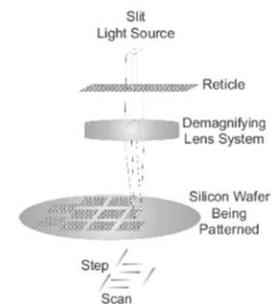


Figure: Configuration and relative motions in a step-and-scan exposure tool

So, this is typically the configuration of a step-and-scan exposure tool that is used in this particular photolithography. So, what are the important things involved? The first thing is the photo masks or reticle. So, these are basically made of fused silica with some chrome patterns, and then comes the exposure mechanism.

It basically uses a step-and-scan process, so how it works is that a slit of light scans across the reticle, which is the mask. Now, the pattern is basically projected onto a photoresist-coated wafer at a reduced feature size. and the feature size gets reduced because of the reduction lenses. So, you basically have a demagnifying lens system that reduces this feature size. Now, this reticle and the wafer can both move simultaneously and precisely to replicate the full die pattern.

So, this is how it works: step and scan, okay? So, once one die is particularly patterned ok. So, you basically allow the system to step to the next die area, and then it is also exposed. This can also be done using the immersion lithography method. So, here a thin layer of water is maintained between the wafer and the objective lens and this basically helps you to increase the resolution and also allows a finer feature patterning. So, if you look into the resolution of this UV photolithography, it is determined by the Rayleigh equation.

Photolithography: Deep UV (DUV) Lithography

➤ The resolution in UV photolithography is determined by the **Rayleigh equation**:

$$W = k_1 \frac{\lambda}{NA}$$

where k_1 : process factor (accounts for resist quality & resolution enhancement techniques)

- **k_1 factor**: Theoretical minimum: 0.25
 - ✓ Practical values: ≥ 0.3 (below is too difficult/expensive)
- This equation defines the smallest printable linewidth (W) based on the wavelength (λ) of exposing light and numerical aperture (NA) of the projection optics.
- According to above eq.:
 - Smaller the wavelength, smaller the feature size.
 - NA : A measure of the optical system's ability to collect and focus light.
A **larger NA is desirable** for achieving smaller features.
 - ✓ Max NA in air: 1.0 (practical limit ~ 0.95)

So, you can write $W = k_1 \frac{\lambda}{NA}$. So, here k_1 is basically the process factor that accounts for the resist quality and the resolution-enhancement technique. So, k_1 the theoretical limit is 0.25 and the practical values are always greater than equal to 0.3 because below this, it is very difficult and the system becomes very expensive.

And in this equation, so W basically represents the smallest printable line width and you

can see It is based on the wavelength of the exposed light and also on the numerical aperture of the projection optics. So, according to this equation smaller the wavelength smaller will be the feature size larger the NA smaller will be with your feature size. Now, what is NA?

It is basically a measure of an optical system's ability to collect and focus light. So, you can see here that a larger NA is always desirable because it will give you a smaller feature size. Typically, the maximum numerical aperture in air is 1, and the practical limit is somewhere around 0.95.

Photolithography: Deep UV (DUV) Lithography

- Thus; with this practical value of NA: (For a typical 193 nm immersion scanner (DUV) lithography)
 - The smallest printable linewidth with a single exposure is around 40 nm (Feature size).
 - Modern DUV photolithography systems employ ArF excimer lasers at 193 nm and conventionally limited to feature sizes.
 - By creative use of different combinations of optical proximity correction (OPC), phase shift, immersion lithography, and multiple patterning:
 - ✓ Extended 193 nm lithography to produce feature sizes significantly reduced to ~ 22 nm. (See in fig)
- Figure shows the historical progression of IC feature sizes and the wavelength of the photolithography light source required to achieve these feature sizes.

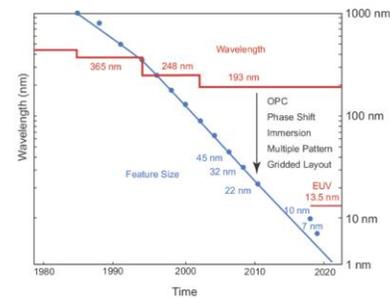


Figure: Historical progression of IC feature size and photolithography technologies

Now, if you put all these practical values on numerical aperture and all the other conditions into your 193-nanometer immersion scanner that is being used for deep ultraviolet lithography, the smallest principle printable line width with a single exposure comes out to be around 40 nanometers. So, that is the minimum feature size. Now modern deep ultraviolet photolithography systems employ these argon fluoride excimer lasers at 193 nanometers. and conventionally limited to this feature size. Now, by the creative use of different combinations of optical proximity correction, phase shift, immersion lithography, and multiple patterning, you can bring down the feature size to even 22 nanometers for the same wavelength.

So, that is also shown here on this particular website where it shows the historical progression of IC feature size and the photolithography technique. So, these are the wavelength scale and you can see the feature size is coming down with years. This particular one also shows the wavelength of the photolithography light source that is required to achieve the correct feature size. This is the boundary of extreme UV, okay.

So, with that, you can go to feature sizes like 10 nanometers, 7 nanometers, and so on.

Okay.

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 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.
- EUVL enables the use of only one mask exposure instead of multi-exposure.
- 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).

Next, we will discuss this extreme UV lithography because it is a much more advanced technique and you can get much shorter feature size because you are using much shorter light source okay which has got a wavelength of only 13.5 nanometer. So, where is it used? This extreme ultraviolet lithography is basically employed to create photo masks and diffraction gratings that have extremely fine features. So, these components are basically essential for applications like holography, laser beam shaping and diffraction-based spectroscopy. Extreme ultraviolet lithography also enables the precise patterning of nanoscale structures that are important for various nanotechnology applications.

This technique enables the use of only one mask exposure instead of multiple exposures. The development of the resist material has become a very critical technical issue in the case of this extreme ultraviolet lithography. So, this resistant material is necessary to have these excellent characteristics like high resolution, high sensitivity, and low line edge roughness.

So now let us look at the extreme ultraviolet lithography system.

Photolithography: Extreme UV Lithography (EUVL)

- EUV lithography tools typically utilize a [plasma source](#) to generate 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.
- EUV's photomasks work in reflective mode.

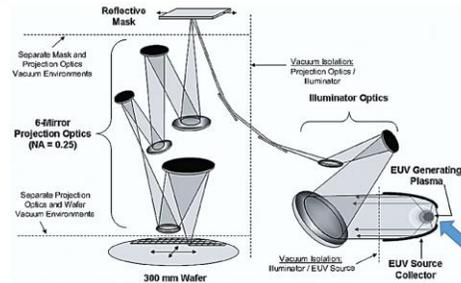


Figure: Extreme Ultra violet Lithography

So typically, this tool utilizes a plasma source to generate 13.5 nanometer photons. And this EUV light from the plasma is gathered using optical elements, which are also known as collectors. And the light from the collector is basically directed into a set of shaping optics that are also collectively known as illumination optics. Now, this light illuminates a photo mask located on a high scan speed vacuum stage. So, the illumination optics basically consist of multilayer-coated normal incidence mirrors and some, you know, grazing incidence mirrors. And if you see here, the photo mask is basically working in reflective mode, Okay.

Photolithography: Extreme UV Lithography (EUVL)

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

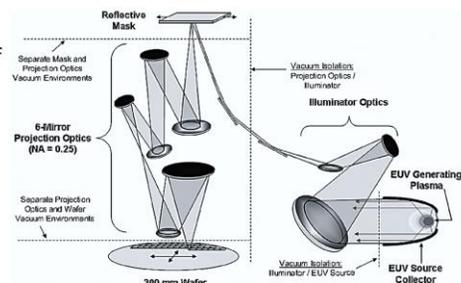


Figure: Extreme Ultra violet Lithography

So, this mask basically consists of a 6-inch square, quarter-inch thick, low thermal expansion material. which has a multi-layer reflective coating on top and an absorbing layer typically chrome etched into the design of the circuit layer. So, the reflected image of this extreme UV mask will then enter the projection optic system Where there will be demagnification, typically a 4 to 1 ratio, okay. So, this projection optics is typically a collection of 6 or more multilayer mirrors, and typically they have a numerical aperture greater than 0.25. What is the job of this?

So, you just need to demagnify your image, okay, or the pattern, and then finally you focus the image on a silicon wafer which is coated with a photosensitive etch-resist chemical emulsion or photoresist. So, this wafer is basically located on a high scan speed vacuum-based stage and you see there are basically isolation from the mask and the projection optics vacuum environment. Here, also there are separate projection optics and wafer vacuum environment separation.

So, after understanding different photolithography techniques, here is a summary in the form of a table that shows the evolution of photolithography techniques over the years.

Photolithography

Table-1: Evolution of Photolithography Technologies

Era / Year	Technology	Key Features	Limitations
1960s-1970s	Contact Printing	Mask in direct contact with wafer; simple setup	Mask damage, contamination, poor resolution
1970s-1980s	Proximity Printing	Small gap (~ 10 – 50 μm) between mask & wafer \rightarrow reduces damage	Still diffraction-limited; $\sim 3 \mu\text{m}$ resolution
1980s-1990s	Projection (Stepper) Lithography	Projects full die image via reduction lens	Limited field size; throughput bottleneck
1990s-Present	Step-and-Scan (DUV 248 nm \rightarrow 193 nm)	Reticle & wafer move synchronously; slit exposure; immersion lithography (water at 193 nm)	Requires high precision; complex optics
2020s-Future	EUV Lithography (13.5 nm)	Extreme resolution (< 7 nm nodes); reflective optics; no lenses	Very high cost: source power, mask defects, stochastic issues

So, from the 1960s and 70s, the technology was contact printing. So, the key features were that the mask is in direct contact with the wafer. And it is a very simple setup, but there are limitations in the form of mask damage, contamination, or poor isolation. Then, in 1970s and 80s people started proximity printing that is by maintaining a small gap like 10 to 50 microns between mask and the wafer So that could reduce the damage. Okay, but this technique was still diffraction limited, so they could only go up to 3 nanometers, 3 micrometers resolution.

In 1980s-90s projection stepper lithography was used, so there it could project full die image via reduction lens, but it had some limitations, like limited field size and throughput bottlenecks. From 1990s till present this scan step and scan technique that is Deep UV 248 nanometer to 193 nanometer is being used. So, the key feature here is that the reticle the mask and the wafer that move simultaneously. There are slit exposure immersion lithography done at you know with water at 193 nanometers. So, there are still some limitations here; the first thing is that it requires high precision and also demands complex optics.

So, from 2020 and in the future, people will be going for extreme UV lithography at 13.5 nanometers. Here you can go up to extreme resolution below 7-nanometer nodes. They are completely based on reflective optics, and no lenses are required, ok. The only problem here is that it is very costly and the source powder masks defects.

There could be like these are the limitations here that they are extremely costly and Then there are issues with the source, power defects in the masks, and stochastic issues.

With that, we look into the other technique of photolithography, which is called laser interference lithography.

Photolithography: Laser Interference Lithography

- **Laser interference lithography (LIL)** is often used to fabricate Optical metamaterials.
 - 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.
 - LIL is a maskless technique that relies on **two or more coherent beams of light** interfering with each other to produce a standing wave intensity pattern on a photoresist-coated substrate.
 - Bright regions (constructive interference) → photoresist is exposed.
 - Dark regions (destructive interference) → photoresist is not exposed.
 - This intensity pattern is then directly transferred into the periodic structure through etching.



Now, in the fabrication of optical metamaterials, this particular technique is commonly used. And this is a key technique for creating intricate patterns of metamaterials. It can also be used to fabricate nanopatterned surfaces for biosensors.

So, it can create highly ordered and controlled micro- and nano-structures on surfaces. And these patterns are very important for tissue engineering applications. So, the laser interference lithography technique basically relies on interference. So, for interference, you require two or more coherent beams to interfere with each other, and then those beams will produce a standing wave pattern. which is basically having dark bright dark bright kind of patterns in the intensity and that will be projected on the photoresist coated substrate.

So, you can see the bright regions that reflect, which tells you that these are areas of constructive interference. So, that is where the photoresist is exposed, and in the dark regions, you will have destructive interference. and that is where the photoresist is not exposed. So, this intensity pattern of the light can be directly transferred to a periodic structure through etching.

So, here you can see the steps for laser interference lithography.

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.

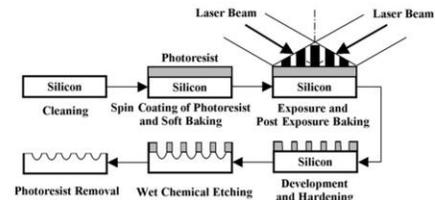


Figure: Laser interference Lithography

The first process, or the first step in this process, is cleaning. So, the silicon wafers are basically cleaned ultrasonically in acetone, absolute alcohol, and deionized water for 10 minutes. and then baked in a drying oven at 150 degrees centigrade for half an hour to ensure an absolutely dry surface. After that, you do the spin coating of photoresist and soft baking. So, a positive photoresist is basically spin-coated on the polished surface of the silicon wafer using a two-stage spinning scheme.

at the room temperature 25 degree centigrade. A spinning speed of 500 rpm and duration of 30 second are first utilized in the first stage followed by a second stage of spinning Where the speed is 10 times 5000 rpm, and the duration is also doubled to 60 seconds.

Next you go to spin coating:

Photolithography: Laser Interference Lithography

o 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.

o 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.

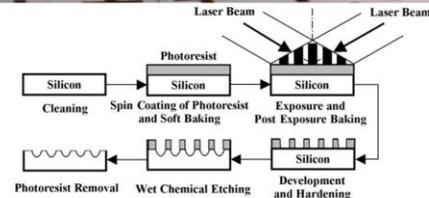


Figure (a) : Laser interference Lithography

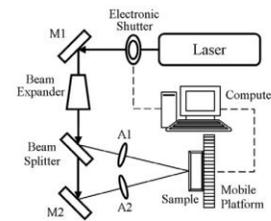


Figure (b) : Optical layout of the laser-interference lithography setup with attenuators A and mirrors M

so, in the spin coating the final photoresist thickness that you develop, is around 1.25 microns, okay. And then what is happening is that the coated silicon wafer is baked in a drying oven at 90 degrees centigrade for around 20 minutes.

This is done to remove residual solvent from the photoresist film, and it also improves the adhesion between the photoresist and the substrate. So, that is typically what is recommended by the photoresist manufacturers. The next step involves exposure and post-exposure baking. So, here you will be seeing that the laser beams, two laser beams are coming from different sides. These are the coherent beams that are interfering with each other.

So, this is the optical layout view of this laser interference lithography setup. Where you see that there is a laser beam expander, beam splitter, and then you get by using the mirrors, okay, this is mirror 1, mirror 2. this is one mirror, this is one attenuator, this beam splitter, so some light is getting reflected. So, you are getting from one laser you are generating two beams which are interfering here and Then you can actually put a pattern on the substrate, right? So, this sample here, as you can see, is fixed on a mobile platform and exposed for a few seconds typically for a dose of 60 to 70 millijoule per centimeter square to a laser of adequate power, ok.

So, this system is incorporated here, ok. So, with this bright dark bright dark kind of pattern ok, you can actually get a nanogroove pattern recorded on the photoresist ok.

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.

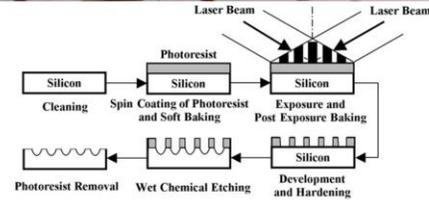


Figure (a) : Laser interference Lithography

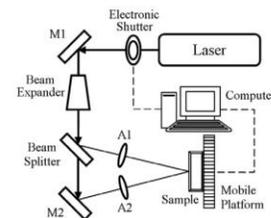


Figure (b) : Optical layout of the laser-interference lithography setup with attenuators A and mirrors M

So, after exposure, the silicon wafers are again baked in a drying oven at 100 degrees centigrade for 10 minutes. To eliminate the standing wave effect in the photoresist film, you finally do the development and hardening. So, the photoresist films are then immersed in positive photoresist developer for 15 seconds to remove the exposed parts. And form the photoresist pattern in the water bath at room temperature; then, they are rinsed with deionized water repeatedly.

Afterwards, the samples are again baked in a drying oven at 120 degrees centigrade for 1 hour. And this basically ensures the addition of the photoresist to the sample surface. So, once this development and hardening are done, you go for wet chemical etching.

Photolithography: Laser Interference Lithography

○ **Wet chemical etching**

- The wafers with patterned photoresist films, which served as etching masks, are immersed 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.

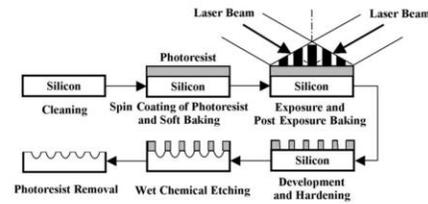


Figure (a) : Laser interference Lithography

So, the wafers that now have patterned photoresist films will serve as etching masks. They are immersed and etched by manual stirring in a mixture solution of 65 to 68 percent nitric acid (HNO_3) and 40 percent hydrofluoric acid, H_2O in this ratio of 2 to 1 is placed in a water bath at room temperature for 60 seconds, okay.

And after etching, the wafers are washed with deionized water, and finally, you have to get rid of this photoresist. So, you go to the final process, which is the photoresist removal. So, here, the residual photoresist film and the reaction products in the textures are basically removed, as you can see like this. So, for that, you use a positive photoresist stripper for 30 minutes.

Okay, and then you dry the wafer in a drying oven at 150 degrees centigrade after it has been ultrasonically cleaned with acetone and deionized water.

So, as you can see, it is a very standard protocol. And this laser interference lithography is well suited for fabricating optical metamaterials that basically requires large area highly periodic structures.

Photolithography: Laser Interference Lithography

- LIL is particularly well-suited for fabricating optical metamaterials that require **large-area, highly periodic structures**.
- The period of the pattern is determined by the laser wavelength and the angle of the interfering beams, giving great flexibility in design.
 - For two-beam interference, the periodicity (Λ) of the pattern is determined by the geometry of the beams:

$$\Lambda = \frac{\lambda}{2\sin\theta} \quad \text{Where: } \lambda = \text{wavelength of laser,}$$

θ = half-angle between the two interfering beams (i.e., angle between one beam and the normal).

- It gives design flexibility:
 - **By changing λ (laser wavelength):** we can scale the entire pattern up or down. Shorter wavelengths \rightarrow smaller features.
 - **By changing θ (beam angle):** we can tune the periodicity continuously without changing the laser.
 - ✓ At $\theta = 90^\circ$ (beams opposite), $\Lambda \approx \lambda/2$ (smallest possible pitch).
 - ✓ At $\theta \rightarrow$ small (beams nearly parallel), Λ becomes very large.

Now, the period of the pattern is basically determined by the laser wavelength and the angle of the interfering beam.

So that is giving the flexibility in know designing or in making different designs. For two-beam interference, the periodicity, which is capital lambda (Λ) of the pattern, is basically governed by this formula; which is $\Lambda = \frac{\lambda}{2\sin\theta}$.

Here, λ is the wavelength of the laser, and θ is basically the half-angle between the two interfering beams, okay. So, you can consider this the angle between one beam and the normal. So, you get a design flexibility here that by changing the laser wavelength of the lambda you can scale up the entire pattern or scale down also.

So, if you go for shorter wavelength you get smaller feature size, if you go for larger wavelength you get larger feature size. Now by changing the angle the beam angle you can also tune the periodicity continuously for the same laser you do not need to change the laser, but you are just change the incident angle of the or of the two or you can say the half angle okay that that you can get different periodicity. So, at lambda equals 90 degrees, the beams are opposite. So, there you can get lambda, capital lambda, that is the periodicity (Λ) $\approx \lambda/2$; that is the smallest possible pitch. And when you have θ equal to very small, that means the beams are nearly parallel; that is the case.

Where your periodicity capital lambda will become very large.

So, with that, we move on to some non-optical lithography techniques; the first one will be e-beam lithography.

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.

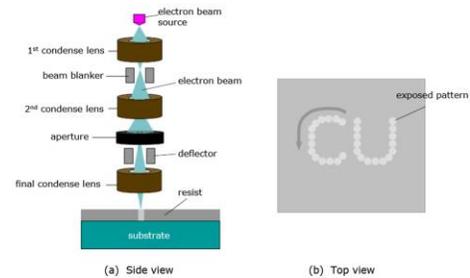


Figure : Electron beam Lithography

So, the name itself suggests that here basically using electron beam okay, for fabricating some patterns, nanoscale patterns. So, e-beam lithography basically utilizes accelerated electron beams focused on an electron-sensitive resist to make the exposure. So, earlier we used to use light, so we used to use photoresist, here you will be using electron beam, so you require electron resist or electron-sensitive resist. So, how it works, you can see that this is the side view of the system; you have an electron beam source then you have condenser lens the electron beam is coming and finally, it is falling on the resist and making the pattern, ok.

So, this is the pattern that was created by exposing an electron beam. So, this is a dot-by-dot fashion in which you can create. So, here you can see that this electron beam spot with a diameter as small as couple of nanometers can be made and it is scanned across the surface of the resist in a dot by dot fashion to generate the pattern that you want. So, electron beam lithography is used in semiconductor manufacturing to create photomasks. And they are also widely used to create intricate patterns for nanophotonic devices and metamaterials.

Interestingly, the resolution of the electron beam technique is also very good.

Non-optical lithography: Electron-beam Lithography

- The resolution of EBL 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.
- So far, the deployment of this technique in manufacturing process still limited due to the difficulty in developing practical electron beam sources.
- 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.

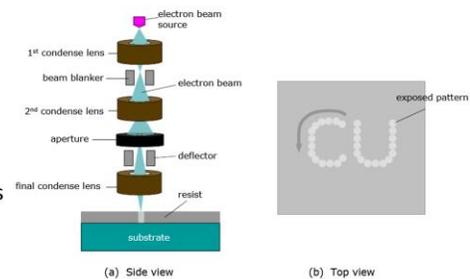


Figure : Electron beam Lithography

You can go down to 5 to 20 nanometers because you are using ultra-short wavelengths of electrons that are on the order of a few nanometers. But the only problem is that the lack of throughput in this technique basically limits the application of this technique only to the research field or mask fabrication. So, EBL lithography is normally used to fabricate prototypes of nanoscale structures and devices.

The large-scale fabrication or manufacturing process using this technique is limited due to the difficulty in developing practical electron beam sources. Recently, scanning electron microscopes have been able to be equipped with some pattern generator modules. So, this basically enabled the scanning of electron beam spot with desired areas or within desired areas to generate some nanoscale patterns in a similar fashion to this electron beam lithography system.

Next, we will discuss FIB milling, which is a focused ion beam technique.

Non-optical lithography: FIB Milling

- **Focused ion beam (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 create nanoscale structures and devices with high precision.
 - 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.
 - A FIB setup is a scientific instrument that resembles a scanning electron microscope (SEM).
 - Rather than a beam of electrons used in SEM, FIB systems use 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.

This is a technique particularly used in the semiconductor industry, material science, and also increasingly in the biological field.

For site-specific analysis, deposition, and ablation of materials. So, as you can understand, FIB can basically create nanoscale structures and devices with high precision. FIB can also be integrated into a system with both electrons. Ion beam columns follow the same feature to be investigated using either of the beams. So, this is a scientific instrument that basically resembles scanning electron microscopy. However, instead of using electron beams, which are typically used in SEM, FIB systems use finely focused beams of ions like gallium.

And that can be operated at low beam current for imaging, and you can also use it at high beam current. For site-specific sputtering or milling applications. And the resolution of FIB lithography is also similar to EBL, which is 5 to 20 nanometers.

Non-optical lithography: FIB Milling

- In FIBM, 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.

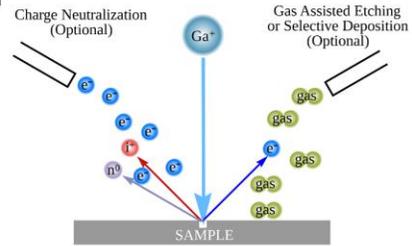


Figure : Focused ion beam principle.

So, in FIB milling, the gallium plus is the primary ion beam that heats the sample surface. and spatters a small amount of material, which basically leaves the surface as either positive or negative secondary ions or neutral ions.

And this primary beam also produces some secondary electrons as the primary beam rasters across the sample surface. the signal from the sputtered ions or secondary electrons is basically collected to form the image. So, at low primary beam current, very little material is sputtered, and you can use the modern FIB systems to achieve an image resolution of around 5 nanometers. And when you increase the primary current okay you can then remove a large amount of material by sputtering and that allows milling which is also precision milling. that allows you to mill the specimen down to sub micrometer or even to nanoscale.

There is another technique in non-optical lithography that is nanoimprint lithography.

Non-optical lithography: Nanoimprint Lithography

➤ **Nanoimprint Lithography (NIL)** is a cutting-edge technique, used to fabricate nanoscale patterns on large surfaces.

- NIL is a promising non-optical technique for high-throughput fabrication.
- A hard master mold with the desired nanostructure pattern is pressed into a soft polymer resist on a substrate.
- The pattern is then solidified, and the mold is removed, leaving the inverse pattern.
 - **Pros:** High throughput, low cost, and capable of creating extremely fine features in a parallel process.
 - **Cons:** The creation of the master mold can be expensive, and alignment for multi-layer devices can be challenging.

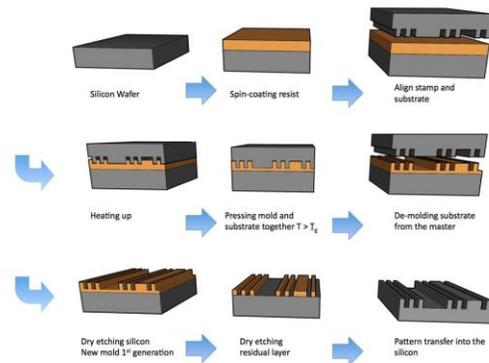


Figure : Nanoimprint lithography

So, here it is basically a cutting-edge technique that can be used to fabricate nanoscale patterns on large substrates. Nano imprint lithography is also a promising non-optical technique because it has got a high throughput, ok So, you require a silicon wafer with a spin coating resist on top, and then you need a hard-master mold with the desired nanopattern. That is basically pressed on the soft polymer resist on a substrate and then you let the let it heat and solidify and then you remove this mold, ok.

So, what happens when you get this pattern ready, okay. So, after that, you can do dry etching to remove this fine bottom layer, and then the pattern through etching can also be transferred onto the silicon. So, what are the pros of this method? High throughput and low cost are capable of creating extremely fine features in a parallel process, but there are some limitations that the creation of the master mold this one can be expensive and the alignment for multiple devices can be challenging.



So, with that, we conclude this lecture. And if you have got any query regarding this lecture, drop an email to this email address mentioning the course name and the lecture number on the subject line. Thank you.