Course Name: Introduction to Microwave and Optical Metamaterials
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Week-12
Lecture-58

Lec 58: Microwave Metamaterial Patterning Methods

Hello everyone, welcome to Lecture 58 of the online course on Introduction to Microwave and Optical Metamaterials. Today's lecture will be on microwave metamaterial patterning methods.

Lecture Outline

- **Overview of Optical lithography (Photolithography) and Non-optical lithography**
- **Lithography Methods for Microwave Metamaterial**
  - **Photolithography techniques**
  - **Inkjet Printing**
    - ❑ **Comparison of Traditional Lithography v/s Inkjet Printing**
  - **PCB−based Lithography**
  - **3D Printing Techniques**

So, here is the lecture outline. We will have a brief overview of optical lithography and photolithography. And different non-optical lithography techniques. And then we will discuss in detail the lithography methods for microwave metamaterials.

We will first start with photolithography techniques, then inkjet printing. We will do a comparison of traditional lithography versus inkjet printing. We will then discuss the PCB-based lithography and 3D printing techniques.

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.

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Source: https://archive.org/details/FundamentalsOfSemiconductorFabricationMaySze2004/page/n35/mode/2up

So, lithography is the process of applying a pattern to a substrate surface.

which is later transferred to the substrate itself. So, when we talk about optical lithography, it basically uses light to replicate a pattern. From a photo mask onto the substrate, similar to the traditional photographic reproduction, okay. So, it basically involves a photosensitive polymer, which is also called photoresist, that is applied to the substrate and When it is exposed to light through the photomask, it basically results in a patterned photoresist. So, various photolithography techniques exist, including contact, projection, immersion, and interference methods.

Which basically uses different types of light, such as UV, deep UV, extreme UV, and X-rays. So, different lights are used for different types of structure resolution that you want to pattern. We will see that later. When we talk about non-optical lithography methods, they basically use the electron beam. So it is called electron beam lithography, or EBL, or ion beams, something like focused ion beam lithography, so FIB, okay.

And then mechanical forces, something like nano-imprint lithography, These are different non-optical lithography methods to create patterns on the resist film. So, each lithography technique has its own advantages and disadvantages. or limitations in terms of resolution, throughput, and suitability for different applications. And that is why all these different methods are important: because they are used in different scenarios. In photolithography, that means you are using light sources; UV light sources you will see that.

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.

These are the widely used ones in photolithography because of their ability to provide better image resolution. And also the availability of UV-sensitive photochemicals. So, mercury vapor lamps are typically the dominant UV light sources used in photolithography. which emit lines at 405 nanometers (h line), 365 nanometers (I line), and 254 nanometers (ok). Among these, the 365 nanometer, which is the I line, is the most commonly used one.

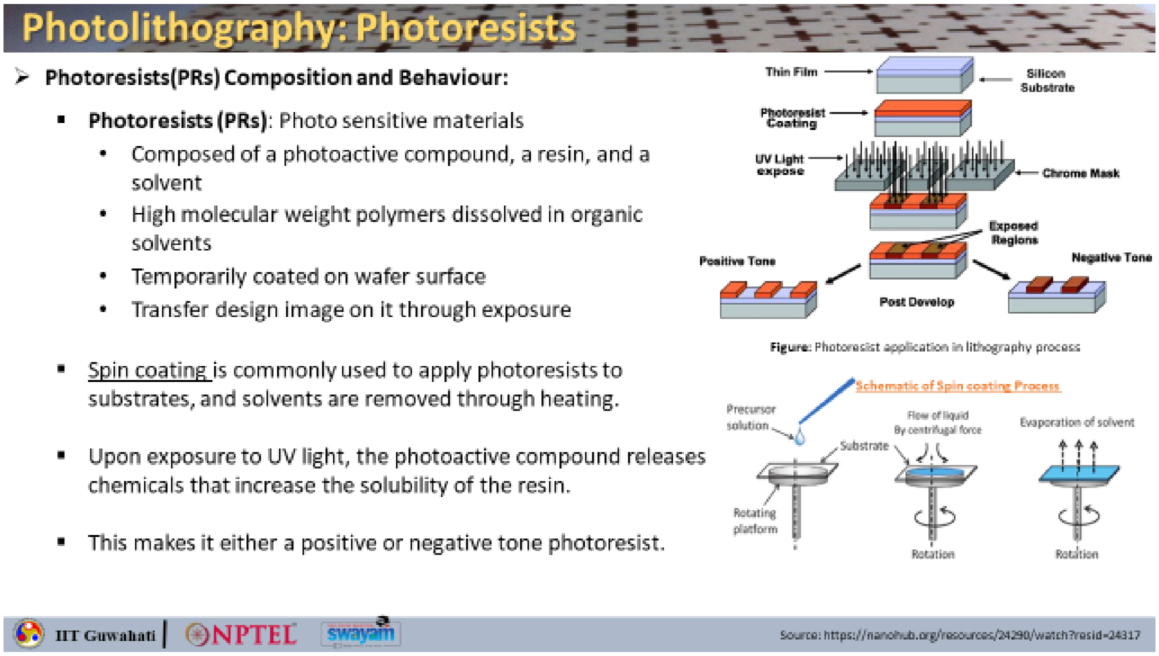
Now, there are deep UV light sources such as excimer lasers that operate at 248 and 193 nanometers. So, these have been adopted to achieve higher resolution in lithography, right. Now, an excimer laser is basically a short form for excited dimer laser. So, it is basically a type of laser that can generate intense UV light. via the use of excited dimers or molecules.

So, unlike most lasers that rely on stimulated emission from atoms or ions, these excimer lasers are Basically, use a combination of noble gases and reactive gases to create a laser medium. Then you have extreme UV sources that are under development at 13.5 nanometers that can help you in advanced lithography applications. So, in lithography, it is critical or crucial to ensure uniform illumination intensity across the entire substrate surface. which basically requires shaping the beam into a flat, speckle-free profile to avoid any undesirable effects.

Now, when I say "speckle-free profile," that basically refers to the desired outcome of the lithographic process. Where the pattern of the image produced on the photosensitive material. which is also called photoresist and should be free from speckles or unwanted noise. These are basically the noises that come from the interference patterns. So, the speckles in the lithographic pattern can basically degrade the quality and precision of the final image, especially.

Where you require very high resolution and fidelity, something like in semiconductor manufacturing. Now, other than the light source, the second important parameter in photolithography is basically the photoresist.

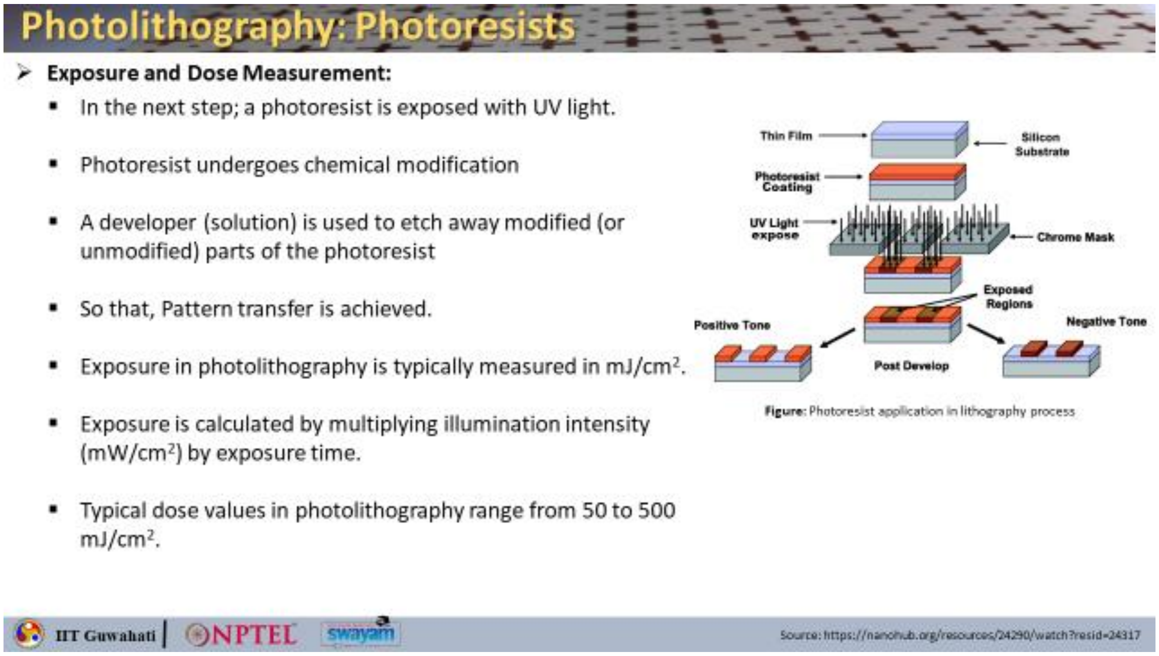
So, photoresist composition and its behavior decide how you are going to do the lithography process.



So, photoresists are nothing but photosensitive materials. They are basically composed of photoactive compounds, resin, and a solvent.

High molecular weight polymers could dissolve in organic solvents, and they are temporarily coated on the wafer substrate. So, this is where you have your silicon substrate, and then you have a thin film on top of that; you do the photoresist coating. Okay, and then whatever the design you want to transfer that you do via you put a chrome mask like this and then you do the UV exposure so that UV light can go through the gaps and hit your photoresist. This is how you are transferring the design from the mask onto the surface.

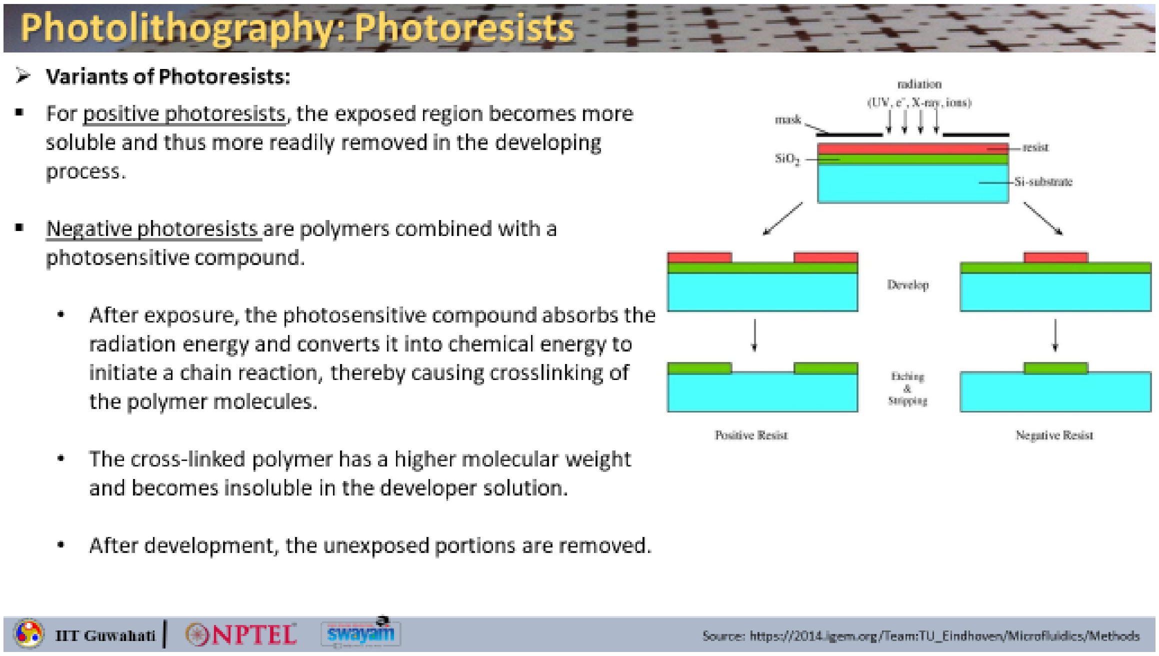
photoresist right. Now, how do you apply the photoresist? You basically use the spin coating method. So, this is nothing but a rotating platform ok on which you have the substrate on top of that you put this precursor solution and then you spin coat it. So, from the centrifugal force, you will get a very uniform spread, and after that, you expose it to UV light. And this photoactive compound will release chemicals that increase the solubility of the resin. So, this can make it so that you can choose either a positive or negative tone photoresist.



So once you put this exposure to the UV light, what is happening to the photoresist? They basically undergo chemical modifications. And then a developer solution is basically used to etch away the modified or unmodified parts of the photoresist. So this is where the exposed regions are. Ok. Now there are two ways of doing it.

So, either you can etch away the exposed parts, or you get the positive tone photoresist, and if these parts only retain. The remaining photoresist that can be removed is called the negative tone photoresist. So, that is how the pattern that you are transferring can be, you know, achieved. So, typically the exposure in photolithography is measured in millijoules per square centimeter, and the exposure is basically calculated. By multiplying the illumination intensity, which is milli-watts per centimeter squared, by the exposure time.

So, you get the millijoule per centimeter squared. And the typical dose in photolithography would range from 50 to 500 millijoules per square centimeter.



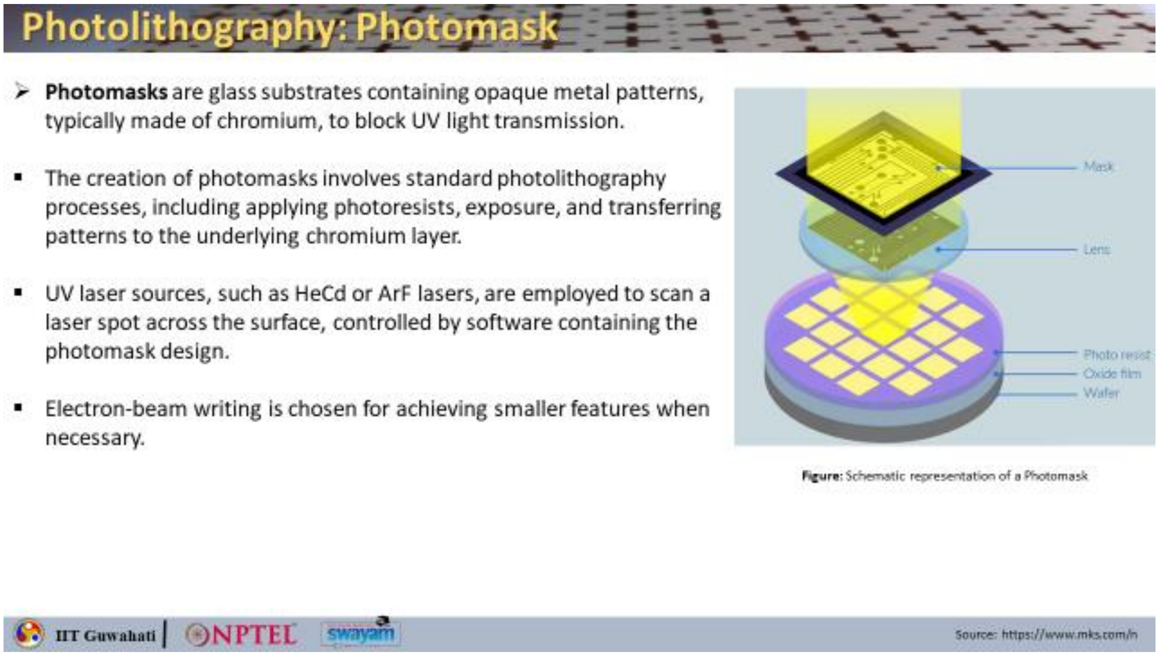
So, as we discussed, there are two variants of photoresist: one is the positive photoresist. So, what happens is that the exposed region becomes more soluble and can be easily removed. In the developing process, okay.

In the case of negative photoresist, there is another way. So, your polymers basically get combined with a photosensitive compound, okay. And this compound basically absorbs the radiation energy and converts it into some sort of chemical energy in a chain reaction. Causing the cross-linking of the polymer molecules. In short, they become, you know, these linked polymers will have a very high molecular weight, and they become insoluble in the developer solution.

So, this part will not dissolve; the remaining will get dissolved, okay? And after the development, the unexposed portions are basically these two that will be removed. Now, if you consider a professional producing materials in the microelectronics industry, he or she would have definitely heard of this negative photoresist. It is an essential tool that is used to create accurate and precise electronic components on various substrates. And a negative photoresist basically serves as an integral layer for successful device fabrication, enabling microfabrication engineers. To develop structures that would otherwise not be achievable with conventional etching methods.

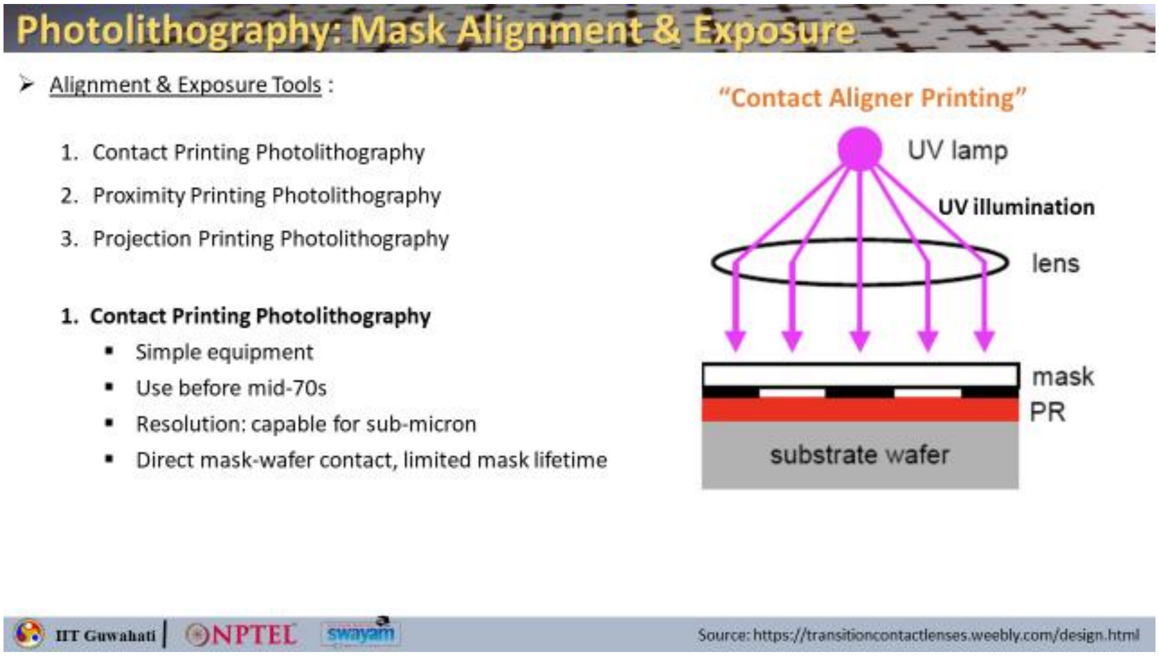
So, understanding how to utilize negative photoresist effectively can make all the difference. So, as you understood that you know negative photoresist is basically a type of photosensitive material That is used in this photolithography process. That can essentially create the pattern on the substrate. So, here you after exposure the solubility of this material increases. So, the developer's solution cannot etch it out right.

So, that is the only difference compared to the positive photoresist.



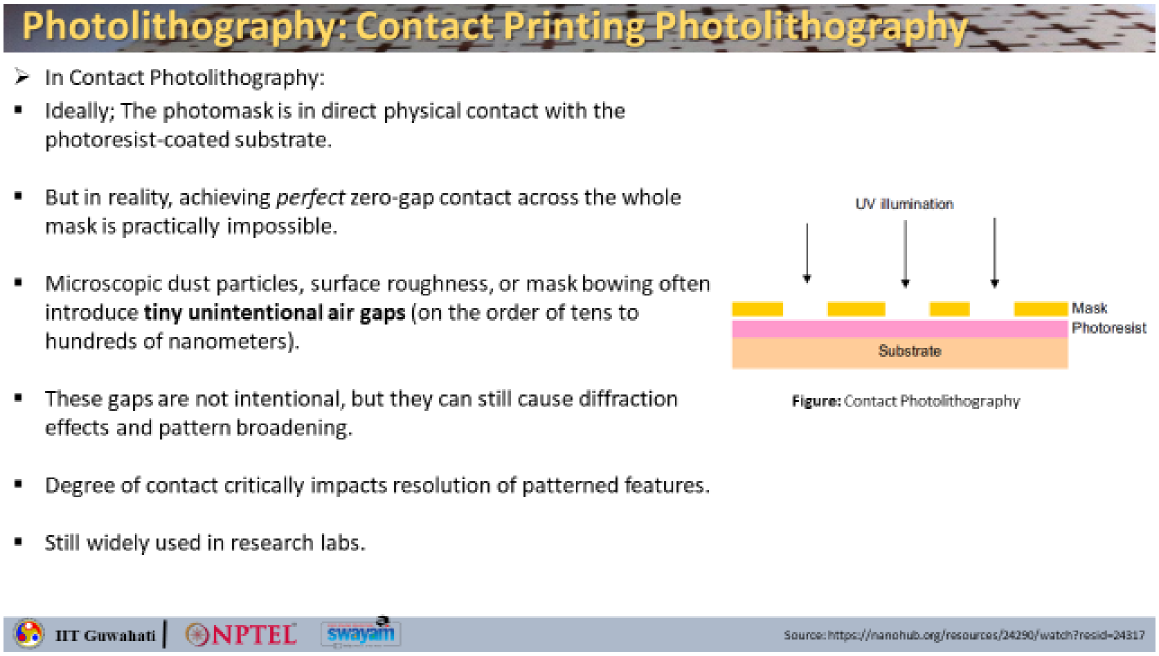
The next important component is the photo mask, okay. So, photo masks are nothing but glass substrates that contain opaque metal patterns typically made of chromium. That could block the UV light transmission, okay. So, this is a schematic representation of a photo mask, and then you have a lens, and this is how these patterns are being transferred onto the photoresist.

Now, the creation of the photo mask basically involves a standard photolithography process where you again need to apply photoresist exposure. And then you transfer the pattern to the underlying chromium layer. And then you use UV light sources such as helium, cadmium, or argon fluoride lasers to typically scan a laser spot across the surface. which is controlled by software containing the photo mask design. And then electron beam lithography can be chosen if there are small features.



So, once that is done, you can think of the mask alignment and the exposure. So, for alignment and exposure tools, there are basically three different types of photolithography, you could say. One is contact printing, then there is proximity printing lithography, and then there is projection printing lithography. So, the first one we will discuss is contact printing photography. So, here you can see it is very simple equipment, okay, that was typically used before the mid-70s, okay.

What is happening here is that the mask is basically in contact, okay? So, there is a direct mask and wafer contact, and that limits the mask's lifeline or lifetime, okay. The resolution is typically submicron. So there is a UV lamp, there is a lens, and then you can allow the light to come through this mask as a parallel wave. But then, because they have contact here, the lifetime of the mask is reduced.



Then you can also see that in this contact photolithography, the photomask basically comes into direct physical contact with the photoresist-coated substrate.

But in reality, you will see that achieving a perfect zero gap across the whole mask is practically impossible. So, typically what gets in between are the microscopic dust particles, or there could be surface roughness. Or the mass may be bowing often due to some irregularity in the surface, and that will introduce some tiny unintentional air gaps. which is typically some tens or hundreds of nanometers. Though these gaps are not intentional, they will still cause some diffraction effects and pattern broadening.

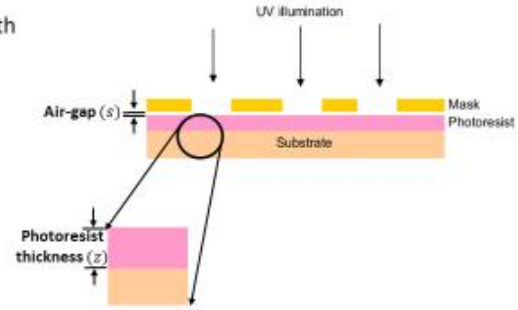
That means the degree of contact critically impacts the resolution of the patterned substrate. So, this kind of work is still used in research laboratories.

Photolithography: Contact Printing Photolithography

- Contact Photolithography
  - Aerial images can be approximated mathematically.
  - Minimum Gaussian aerial image width relates to photoresist thickness (z), air gap (s), and UV wavelength (λ) is:

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

  - Essential for thick photoresists and double-sided alignment/exposure.
  - Applications include advanced 3D packaging, optical devices, and MEMS.
- Challenges
  - Even small unintended air gaps cause diffraction.
  - Leads to pattern enlargement and loss of accuracy.
  - Direct contact causes mask damage and contamination.



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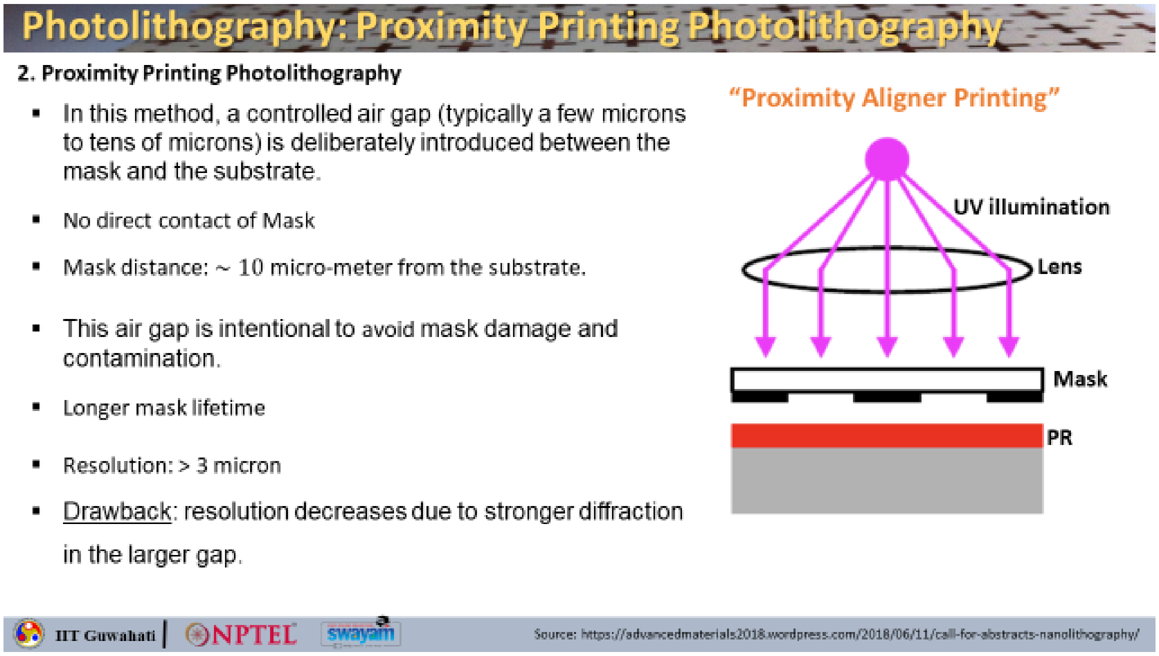
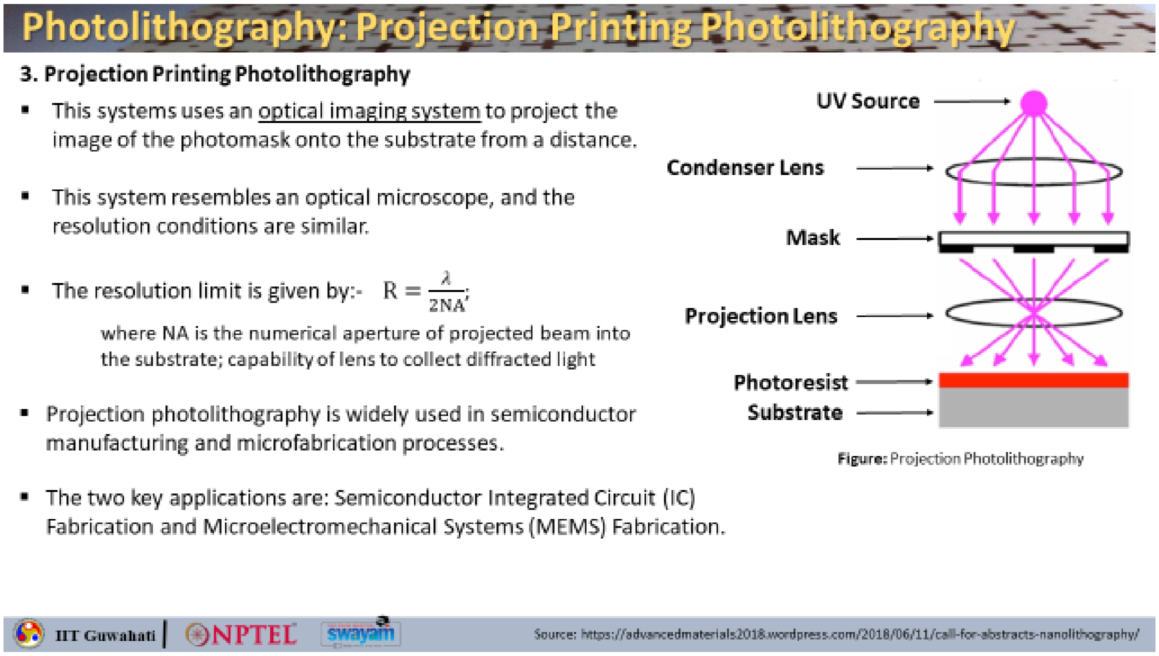
So, here you can see the aerial image that can be approximated mathematically. So, the minimum Gaussian aerial image width can be related to the photoresist thickness z and the air gap thickness s. and the UV wavelength lambda that is being exposed.

So, you can find out the minimum Gaussian aerial image width to be $(W_{\min}) \approx \frac{3}{2}\sqrt{\lambda\left(s+\frac{z}{2}\right)}$, ok. Now, it is essential for thick photoresist and double-sided alignment exposure to be okay. So, this particular contact lithography and what are the applications that include advanced 3D packaging, optical devices and MEMS. Now, there are some challenges, as I mentioned, that because of these small unintended air gaps, they will have some diffraction effects. In some cases, you can see that the patterns are getting enlarged, or there is a loss of accuracy, and most importantly, Because there is direct contact, the mask will get damaged and contaminated.



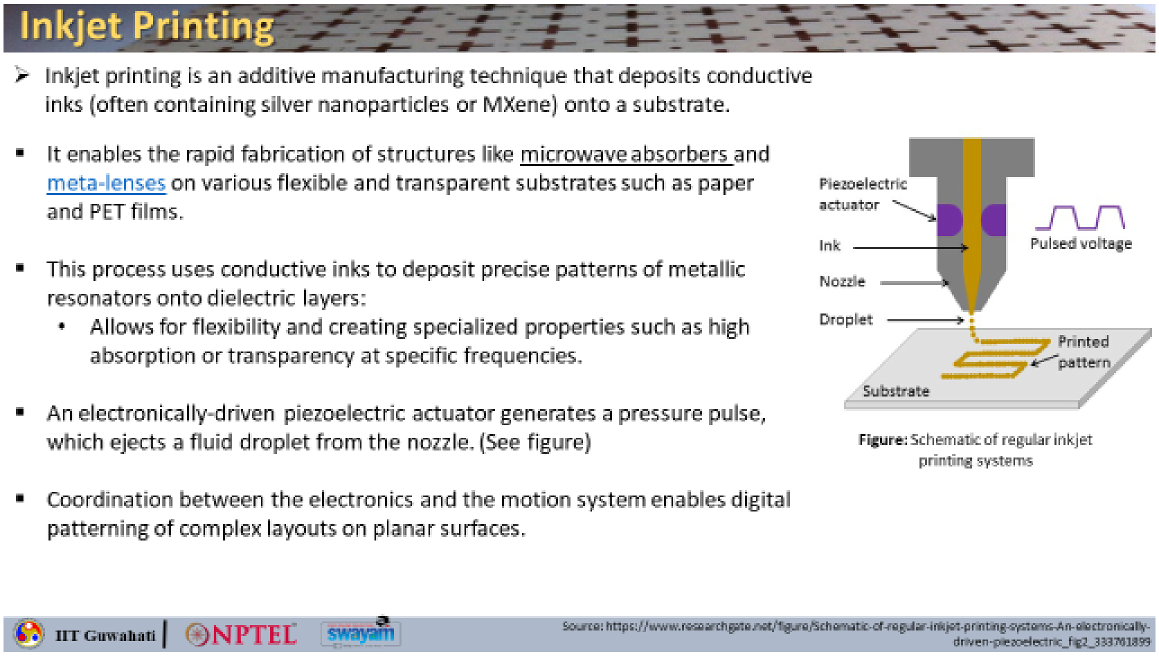
So, the next method, which is better than this one, will be the proximity printing photolithography. As the name itself suggests, in this method you introduce a controlled air gap, typically a few microns or, you could say, tens of microns. That is deliberately introduced between the mask and the substrate. So, PR is the photoresist layer; this is the substrate, and this is the mask, okay. You see, these are the openings through which light can get in, and this is the pattern that will be transferred.

So, the good thing here is that there is no direct contact of the mask, and the mask distance is typically 10 micrometers from the substrate. So, here the air cap is intentional, and it can avoid mask damage and contamination. So, it results in a longer mask lifetime. The resolution is typically greater than 3 microns in this case. So, what is the drawback in this particular method is that the resolution decreases due to stronger diffraction because you are maintaining a larger cap ok.



The third one is projection-printing lithography. So, here you have this mask; up till here it is the same, okay. Then you have a projection length, okay. So, this is the new optical imaging system that you are using in this particular method to project. The image of the photo mask onto the substrate from a distance, okay. So, this is just like an optical microscope, and the resolution conditions are also very similar. So, here the resolution limit is given by $R = \frac{\lambda}{2NA}$. NA is basically the numerical aperture of the projected beam onto the substrate.

That basically tells you about the capability of the lens to collect the diffracted light. So, projection lithography is widely used in semiconductor manufacturing and microfabrication processes. So, the main two applications are semiconductor IC fabrication and microelectromechanical systems, or MEMS, fabrication. Here you get very good resolution, right.

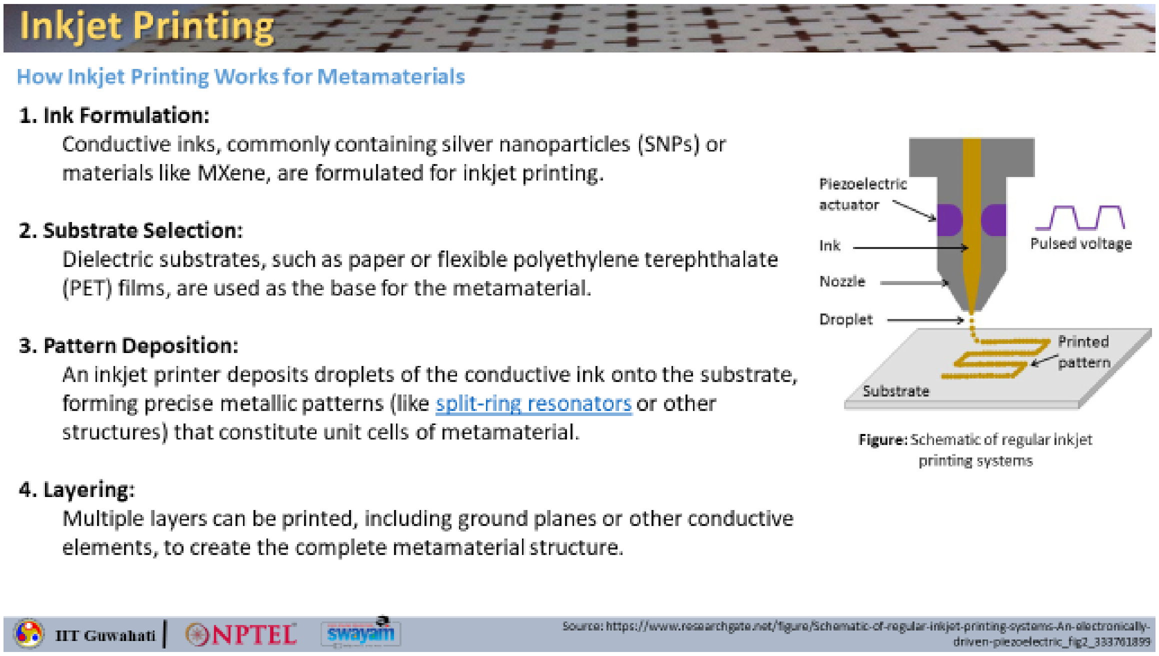


So, the next method we will discuss is inkjet printing. So, inkjet printing is an additive manufacturing technique that basically deposits conductive inks often.

which contains silver nanoparticles or a magazine onto a substrate. So, it is basically a low-cost and direct additive manufacturing technique that can be used for creating materials. It enables the rapid fabrication of structures like microwave absorbers and metal lenses on various flexible substrates. Transparent substrates such as paper and PET films. So, this particular process basically uses conductive ink to deposit a precise pattern of metallic resonators on a dielectric substrate.

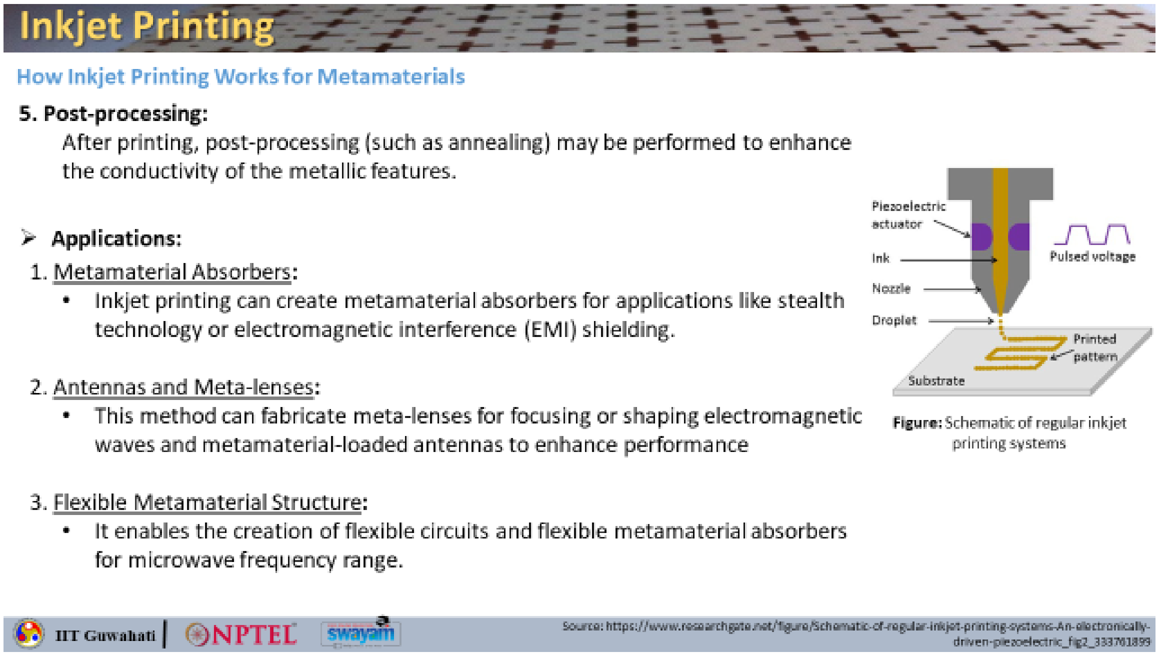
So, this allows for flexibility and creating specialized properties such as high absorption or transparency at specific frequencies. So, here you can see that an electrically driven piezoelectric accelerator can basically generate a pressure pulse. Which will eject a fluid droplet from the nozzle and coordinate between the electronics. And the motion system will enable digital patterning of complex layouts on planar substrates.

Now we will see how inkjet printing works with metamaterials.



So, the first thing would be the ink formation. So, you consider conductive inks that commonly contain silver nanoparticles or materials like magazine. That is typically used for inkjet printing, and then you do the substrate selection. So, you go for dielectric substrates such as paper or flexible polyethylene terephthalate. Or you can say PET in short for PD films that can be used as the base for the metamaterials.

And the third step would be pattern deposition. So, here the inkjet printer basically deposits droplets of the conductive ink on your substrate. Forming a precise metallic pattern just like you can see here, or you can create any splitting resonators. or any other structures that constitute unit cells of the metamaterial. And next, you can also think of layering, which means multiple layers can be printed, including ground planes. or other conductive elements that can create a complete metamaterial structure.

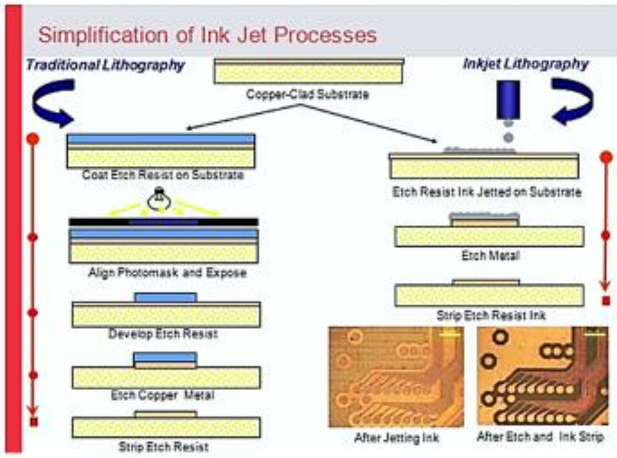


Next, after printing is done, you have to post-process, that is, you have to do annealing to enhance the conductivity of the metallic features. So, that is how you do the printing of the metamaterials. So, where are the applications? First, you can make metamaterial absorbers using this inkjet printing. So, inkjet printing can create metamaterial absorbers for various interesting applications, such as stealth technology. or electromagnetic shielding that is electromagnetic interference (EMI) shielding.

You can also use them for antennas and metal lenses. So, you can fabricate metal lenses for focusing or shaping electromagnetic waves and metamaterial-based antennas. To enhance performance, as we already discussed in this course earlier. You can also think of a flexible metamaterial structure. So, it basically enables the creation of flexible circuits and flexible metamaterial absorbers for the microwave frequency range.

So, here is a comparison of traditional lithography versus the inkjet printing method.

Comparison of Traditional lithography v/s Inkjet Printing



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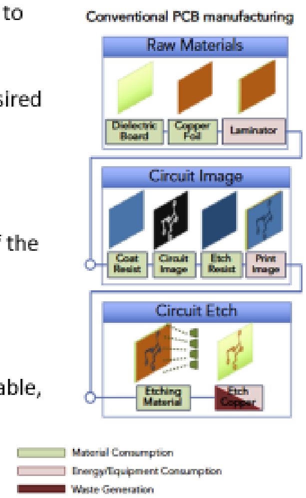
Source: https://www.dupont.com/blogs/inkjet-printing-for-eco-friendly-pcb-etch-processes.html

You start with a copper-clad substrate in both cases; then, in the traditional lithography method, you first coat the etch resist on the substrate. then you align the photo mask and do the exposure UV exposure and then you develop the etch resist ok. On top of that, you have to remove the copper metal, and then you also remove this etch resist, and you get your pattern here. In the case of inkjet lithography, what you do is etch the resist jetted on the substrate. So, you put it like this on top of that after that is done okay you can basically etch the copper metal okay And then you strip this etch resist ink, okay, and you’ve got the pattern done.

So, this is how it will typically look after jetting ink and after etching and the ink strip. So, this is how you get your final PCB or the metal materials fabricated.

PCB—based Lithography

- PCB lithography is a subtractive manufacturing method that uses a series of steps to create metamaterial structures on a PCB board.
  - It is a technique for creating 2D or planar metamaterials by etching or printing desired patterns onto a substrate (usually an FR-4 board).
  - It works by transferring a desired pattern onto a resist-coated substrate.
  - The unwanted material is then **etched** away, leaving behind the precise pattern of the metamaterial.
  - It enables precise creation of microwave and electromagnetic structures on PCBs.
  - It's a key manufacturing technique for microwave metamaterials because it's scalable, cost-effective and produces large-scale, planar structures needed for microwave frequencies.



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Now, we will look into PCB-based lithography. So, PCB is a printed circuit board; PCB lithography is a subtractive manufacturing method. That basically uses a series of steps to create metamaterial structures on a PCB.

So, it is a technique for creating 2D or planar metamaterials by etching or printing desired patterns onto a substrate, typically on an FR-4 board. So, it works by transferring a desired pattern onto a resist-coated substrate. So, this is how the raw material for the PCB will look. So, you start with the dielectric board, then you take copper foil on both sides or one side, and then you send it to the laminator. So, you get the copper laminator on dielectric board, ok and then you have the coat the resist being coated here And then you put the circuit image on top of that, you etch the resist, and you print the image, okay.

And finally, you do the circuit etching, which means you etch the material out. So, what you are left with is only the pattern on the dielectric, okay. So, this is basically the copper pattern on the dielectric, right? So, this is how the unvented material will be etched away, and you will get the precise pattern on the metamaterial. So why is it important? Because it enables the precise creation of microwave and electromagnetic structures on PCBs. And it is a key manufacturing technique for microwave metamaterials because it is scalable and cost-effective.

And it produces large-scale planar substrates that are needed for microwave frequencies.

Now, what are the key steps in PCB fabrication?

PCB—based Lithography

- Key Steps in PCB Fabrication: The process transforms a digital design into a physical board through a series of additive and subtractive steps:

1. Design the PCB Layout

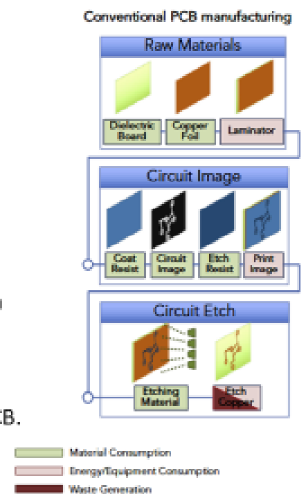
- Create the Circuit: Start by designing your circuit using electronics design automation (EDA) software, creating the schematic and converting it into a PCB layout with component footprints and routing.

2. Print the Layout

- Print the Design: Print the final PCB layout onto a transfer paper or transparency sheet using a laser printer or inkjet printer. Ensure the print is a mirror image if using the toner transfer method.

3. Prepare the Copper Board

- Cut the Board: Cut a copper-clad blank board to the required size for your PCB.
- Clean the surface of the copper-clad board to remove any dirt or oxidation, lightly sanding it with fine-grit sandpaper to achieve a shiny surface.



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The process essentially transforms a digital design into a physical board through a series of additive and subtractive steps. So, you start with the dielectric board and a copper foil, and then you finally get a dielectric board on which a copper pattern is basically printed, right. So, what is the first step? Here, you have to go and design the PCB layout, so that you can create the circuit. For the design of the metamaterial using any electronic design automation (EDA) software, okay.

So, there you create the schematic and convert it into a PCB layout. With the component footprint and routing. So once it is done, you print the layout, okay? So that means you print the design. So that means you are basically printing the final PCB layout onto transfer paper or a transparency sheet using a laser printer or an inkjet printer. So this print is the mirror image if you are using the toner transfer method, okay.

And then you prepare the copper board, okay. So, you need to cut the board. So, there is a you take this copper-clad blank board and you cut it to your desired size of the PCB and Then you have to clean the surface of the copper-clad board to make sure that there is no dirt or oxidation, okay. Standing on it. So, you can also use fine grit sandpaper; you can do a little bit of sanding to achieve a shiny surface.

PCB—based Lithography

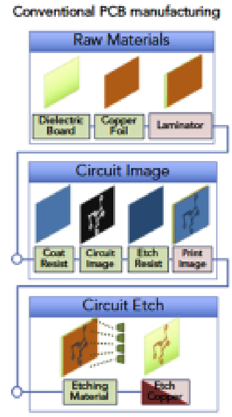
4. Lamination (for multi-layer boards): For more complex metamaterials, multiple patterned layers are stacked and bonded together under heat and pressure to create a single, multi-layer board.

5. Transfer the Layout

- Toner Transfer: For this method, place the printed design face-down onto the clean copper surface and use a hot iron (no steam) to iron the paper onto the board, transferring the toner to the copper.
- Inkjet Method: The layout can be directly printed onto the board using an inkjet printer.

6. Apply the Etch Resist: After transferring, immerse the board in water to peel off the paper, revealing the toner or ink pattern on the copper. This pattern acts as an etch resist, protecting the copper traces that will form the circuit.

7. Etching: The unwanted copper is chemically etched away using a corrosive solution, leaving behind only the desired conductive traces that form the metamaterial's pattern.



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So, you can also go for lamination, and do you know about the multiple layer boards that are required for complex metamaterials? Where you have multiple pattern layers stacked and bonded together under heat and pressure to create a single multi-layer board.

So, you can also do the lamination. Okay, finally you transfer the layout, so you can also use toner transfer in this method. You basically place the printed design face down. onto a clean copper surface, and then you use a hot iron with no steam to basically iron the paper onto the board. And that will transfer the toner to the copper, right? Other methods include the inkjet method that we have just seen, where you can directly print the layout using conductive ink with the inkjet printer.

And once the design has been done, the last step is this etching. So, you have to apply the etch resist for transferring; you have followed this method, and after it is done, you basically immerse your board in water. To peel off the paper that will reveal the toner or ink pattern on the copper. So, this pattern will basically act like an etch resist, protecting the copper traces that are going to form the circuit. Finally, you do the etching that is present here. So, the unwanted copper pattern is basically chemically etched away using a corrosive solution,

Leaving behind the desired conductive traces that will form the metamaterial.

3D Printing Techniques

- **3D Printing Techniques: Additive Manufacturing (AM) Techniques**
  - 3D printing offers a way to create complex, three-dimensional microwave metamaterials that are difficult to fabricate with conventional planar methods (PCB-based method, inkjet printing, lithography).
- **Process:** This technique builds metamaterial structures layer by layer.
  - Common approach:
    - Print dielectric polymer structure with standard 3D printer.
    - Apply conductive coating via sputtering or electroless plating.
    - Advanced option: use conductive filaments to directly print metallic parts.
- **Advantages:**
    - Provides design freedom in the z-direction.
    - Well-suited for rapid prototyping, low cost.
    - Enables creation of volumetric structures and gradient index (non-planar) lenses.
    - Scalability for large structures (microwave antennas, radomes).

Source: Xie, Yangbo, et al. "Microwave metamaterials made by fused deposition 3D printing of a highly conductive copper-based filament" *Applied Physics Letters* 110.18 (2017).

The last important technique that we will be discussing today is the 3D printing technique. So, they are basically also additive manufacturing techniques. So, 3D printing basically offers a way to create complex three-dimensional microwave metamaterials. that are basically difficult to fabricate using conventional planar methods such as PCB-based methods, inkjet printing, or lithography. So, in this 3D printing method, the technique basically uses metamaterial structures, layer by layer, building.

So, the common approach is that you print a dielectric polymer structure with a standard 3D printer. Then you apply conductive coating by spattering or through electroless plating. You can also use some advanced options where conductive filaments can be used to directly print metallic parts. What are the advantages? Here, you can have some design freedom in the Z direction.

So, it is well-suited for rapid prototyping and low cost. and it enables in our creation of volumetric structures and gradient index that is non-planar lenses. So, they are also suitable for large structures like microwave antennas and radomes.

3D Printing Techniques

- **3D Printing Techniques: Additive Manufacturing (AM) Techniques**
  - **Applications:** 3D printing is used to create microwave lenses, complex antennas, and broadband absorbers with unique three-dimensional geometries.

- Few 3D Printing (AM) Techniques:
  1. Fused Deposition Modeling (FDM): Uses thermoplastic filaments (PLA, ABS, PETG).
     - Dielectric structures are printed, then metalized (via sputtering, silver paint, or electroless plating) to create conductive features.
     - Example: 3D-printed dielectric scaffolds coated with copper for split-ring resonators.
  2. Stereolithography (SLA) / Digital Light Processing (DLP): Uses photopolymer resins cured by UV lasers or projectors.
     - Provides higher resolution (~25–100 μm) compared to FDM.
     - Useful for gradient dielectric metamaterials or subwavelength lattice structures.
  3. Selective Laser Melting (SLM): Allows fabrication of all-dielectric MMs or direct metal resonators.
     - High mechanical strength, good for antennas and waveguide-based metamaterials.

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Source: Xie, Yangbo, et al. "Microwave metamaterials made by fused deposition 3D printing of a highly conductive copper-based filament." *Applied Physics Letters* 110.18 (2017).

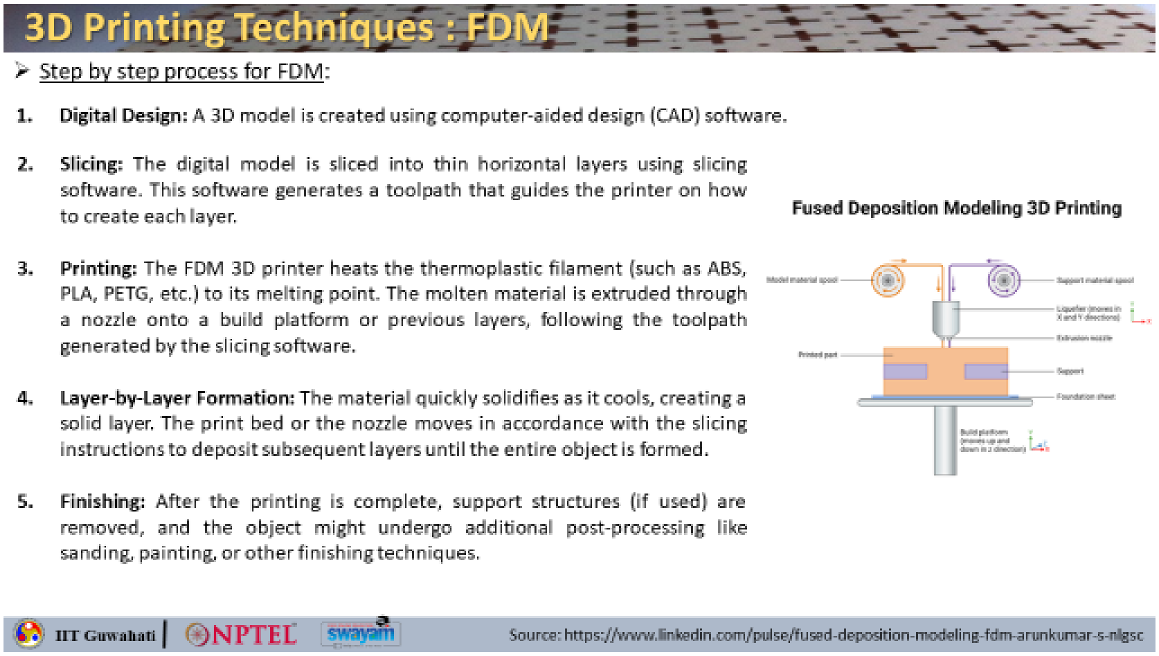
So, the applications of 3D printing techniques can now create microwave lenses. Complex antennas and broadband absorbers with unique three-dimensional geometries.

So, there are a few 3D printing techniques. The first one is called fused deposition modeling, which basically uses thermoplastic filaments such as PLA (polylactic acid). ABS, which is acrylonitrile butadiene styrene, and PETG, which is polyethylene terephthalate glycol modified, okay. So, these dielectric structures are basically printed using this method and Then metallized by sputtering, silver paint or electroplating creates the conductive features. One example could be a 3D-printed dielectric scaffold coated with copper for the split-ring resonators.

Then you can also think of stereolithography (SLA) or digital light processing (DLP). They basically use photopolymer resin cured by UV lasers or projectors. So, they provide higher resolution 25 to 100 micrometer as compared to FDM fused deposition modeling. Okay. And this SLA or DLP is useful for gradient dielectric metamaterials or sub-wavelength lattice structures.

The third method is selective laser melting. So, this allows the fabrication of all-dielectric metamaterials or direct metal resonators. So, high mechanical strength can be achieved. These are good for antennas and also for waveguide-based metamaterials. So we'll look into one of these FDMs first.

So how does it work?



So this is the step-by-step process for FDM. So you have the digital design. So that is a 3D model that is created using a computer-aided design or CAD software. Then you do the slicing. So, the digital model is basically sliced into thin, horizontal layers using slicing software. So, this software basically generates a toolpath that guides the printer on how to create each layer.

Okay, and then you have to do the printing. So, this is FDM 3D printing. So, this 3D printer basically heats the thermoplastic filaments, such as ABS, PLA, or PETG, to their melting point. So, it basically takes the support material spool, and this is the model material spool like this. Then this is a liquefier that moves in the x and y directions, and these are the extrusion nozzles. This is how you print the parts, okay? and this is the platform which can move up and down in the z direction right.

So, this is the foundation sheet on which it was fabricated. So, what happens is that when you put these filaments in, the molten metals are basically extruded, as you can see here through the nozzles. onto this build platform, or you can say on the previous layer, following the tool path that is generated by the slicing software. Then you will have a layer-by-layer formation where the material basically solidifies quickly as it cools down, and it creates a solid layer. The print bed or the nozzle basically moves in accordance with the slicing instructions to deposit subsequent layers until the entire object is formed. And after the printing is complete, the support structure, if it is used, will be removed, and the object might undergo.

Some additional post-processing, like sanding, painting, or other finishing techniques, will give you the final product.

3D Printing Techniques : FDM

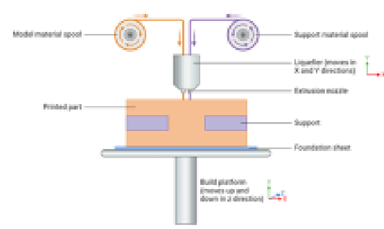
- Fused Deposition Modeling (FDM) is an additive manufacturing technology used for 3D printing.
- FDM works by melting and extruding thermoplastic filaments layer by layer to create a three-dimensional object.

➢ Advantages of FDM : Most commonly used 3D printing processes due to its accessibility, cost-effectiveness, and versatility.

➢ Limitations of FDM:

1. **Layer Resolution**: FDM prints can sometimes have visible layer lines, affecting the surface finish.
2. **Support Structures**: Objects with overhangs or complex shapes may require support structures, which need to be removed after printing, leading to additional finishing work.

Fused Deposition Modeling 3D Printing



So, what we saw is that FDM is an additive manufacturing technology that basically uses 3D printing. So, it works by melting and extruding the thermoplastic filaments layer by layer, and it creates a three-dimensional object. So, the advantages, as you can think of, are that it is using the 3D printing method.

So, it is more accessible, cost-effective, and versatile. However, there are some limitations. The first one is the layer's resolution. FDM prints can sometimes have, you know, visible layer lines, affecting the surface finish. And also, there may be some support structures, something like objects with overhangs. A complex shape that may be required to support the structure which needs to be removed after printing.

So, you need to do some additional finishing work to create the final product.

So, with that, we conclude our lecture. If you have got any queries, drop an email to this email address: deb.sikdar@iitg.ac.in. Thank you.