

Microrobotics

Prof. Palani Iyamperumal Anand

Department of Mechanical Engineering

Indian Institute of Technology, Indore

Week- 03

Lecture No- 13

MicroMechanics System Design (Micro-Fabrication of Micro Robots) - Module 03

From the previous module, as far as this particular case is concerned, there is a kind of measurand involved. So three parts are involved in it. One is a kind of measurand fluid inlet, and then there is going to be a silicon die with a diaphragm. After that, there is a constrained base available, and then there is a kind of measurand fluid inlet that is available. In this case, what we are trying to do is demonstrate that a backside pressure is being generated through this cavity, whereas this is a configuration where a front side pressure exists. So in this front side pressure, what we have is a measuring fluid that is kept as an inlet, and through this inlet, a pressurized fluid enters. The cavity can be efficiently used for the pressure within the cavity using the system. This is a very good example of developing a kind of micro pressure sensor.

Etching → top down approach

- One of the most important microfabrication process, etching involves the removal of materials in desired areas by physical or chemical means.
- It is a way to establish permanent patterns developed at the substrate surface by photolithography.
- In micromachining, etching is used to shape the geometry of micro components in MEMS and microsystems.

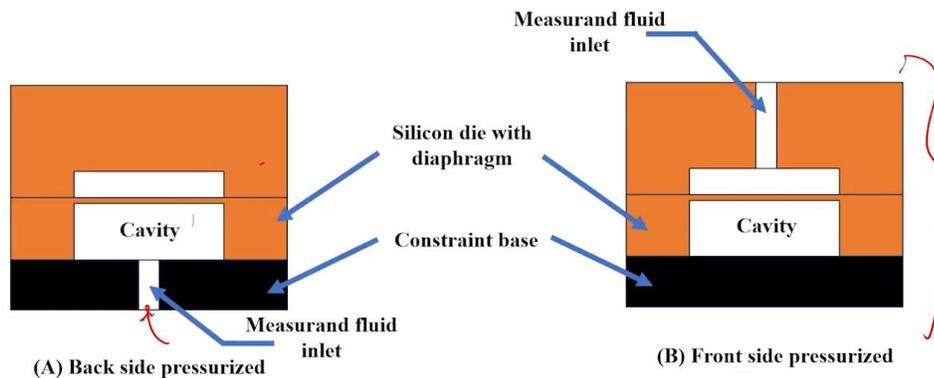
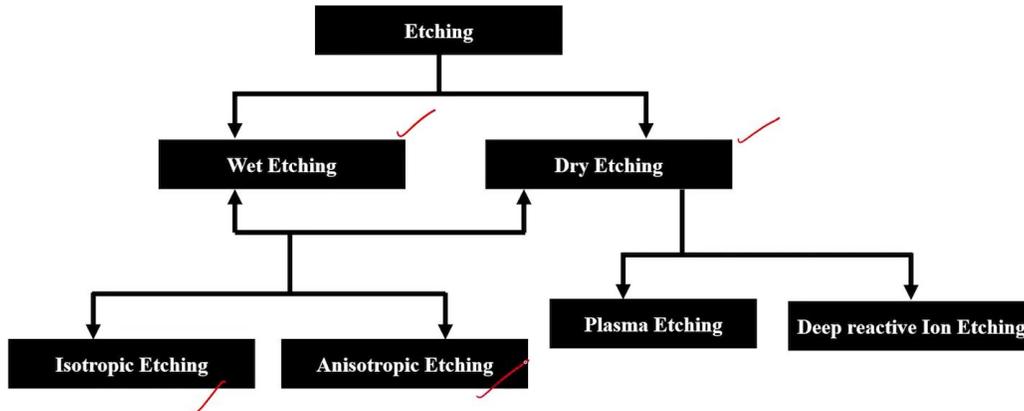


Fig. cross section of micro-pressure sensor

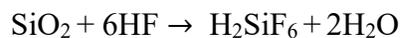
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The etching process is classified into two types: one is the wet etching process and the other is the dry etching process. In the case of the wet etching process or the dry etching

process, it is further classified into isotropic etching and anisotropic etching. However, the dry etching process is classified into plasma etching or deep reactive ion etching.



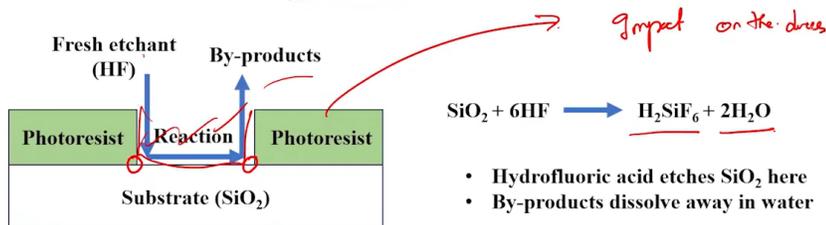
The wet etching process is also called a chemical etching process as it involves a kind of solution, either with a dilute chemical or certain amounts of acid to dissolve the substrate. Let us understand through an example: take a dilute hydrofluoric (HF) solution, which is used to dissolve SiO₂, Si₃N₄, and polycrystalline silicon, whereas potassium hydroxide (KOH) is used for etching the silicon substrates. In order to create this structure, a photoresist is initially deposited over the substrate, and then a fresh etchant is made to pass through this reaction to react with the photoresist, ultimately resulting in a byproduct and a structure as mentioned here. It's a kind of etching that is being performed on this photoresist layer. The overall mechanism of it,



The hydrofluoric acid etches the silicon oxide here, and the byproduct dissolves the overall content in the water. The rate of etching typically depends on the substrate material to be etched, the concentration of the chemical reactant in the solution, and the temperature of the solution. However, the major disadvantage of wet chemical etching for pattern transfer is the undercutting of the layer underneath the mask, resulting in a loss of resolution in the etch pattern; thus, instead of this chemical etching, dry etching can be explored. So this undercutting is nothing but sometimes here at this curved surface; it might not be a proper cut; it might be a kind of curved surface that may exhibit.

Wet Etching

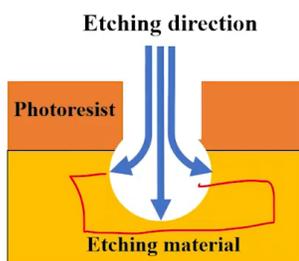
- It is also known as chemical etching process and involves using solutions with diluted chemicals to dissolve substrates.
- For instance, diluted hydrofluoric(HF) solution is used to dissolve SiO_2 , Si_3N_4 , and polycrystalline silicon, whereas potassium peroxide (KOH) is used to etch silicon substrates



- The rate of etching typically depends on **(a) substrate materials to be etched** , **(b) concentration of chemical reactants in the solution** and **(c) Temperature of the solution**.
- Major disadvantage of wet chemical etching for pattern transfer is the undercutting of the layer underneath the mask, resulting in a loss of resolution in the etched pattern and thus dry etching is explored.

So when a curved surface gets exhibits, what happens is it will have an impact on the devices, this will result in a certain amount of failure in the system. This kind of process will result in a loss of resolution and may also degrade the functionality of our system. Now, let us see the overall classification of this etching process. One set of etching is called isotropic etching. Isotropic etching is a process that removes material from the surface in all directions at an equal rate.

Isotropic Etching

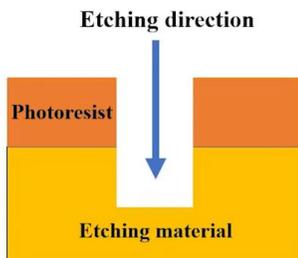


- Isotropic etching is a process that removes material from a surface in all directions at an equal rate.
- It is an **orientation independent** etching technique.
- Performed for substrates made of homogeneous and isotropic materials where chemical etchants attacks the material uniformly in all directions.
- **It is hardly desirable in micromanufacturing because of the lack of control of finished geometry of the workpiece.**

Based on the requirements, such as having a curved structure or having a structure similar to the one in the figure, try to pump the etching medium inside it. That etching medium will efficiently etch the material, and finally, we will get a required framework or structure based on our functionality. One of the important aspects of this process is that orientation is independent of the etching technique, and it is performed for the substrate, which is made out of homogeneous and isotropic material, in such a way that the material

is uniform throughout. In certain cases, for example, wherever we have a kind of single crystal structure, such isotropic etching may have an impact. In the case of single crystal etching, this kind of wet chemical etching will have an impact on the overall crystal structure, etc., which can be efficiently eradicated using a dry etching process. However, from a geometrical perspective, these chemical etchants attack the material uniformly, which will be helpful in etching the layer in all directions. One important point of using such a kind of isotropic etching process is that there is no need for a post-treatment. It is hardly desirable in micro-manufacturing because of the lack of control over the finish geometry of the workpiece. The anisotropic etching is a subtractive microfabrication technique that aims to preferentially remove a material in a specific direction, either in a lateral direction or in a linear direction.

Anisotropic Etching



- Anisotropic etching is a subtractive microfabrication technique that aims to preferentially remove a material in specific directions.
- It is used to create precise shapes like sharp corners, flat surfaces, and deep cavities.
- Anisotropic etching is used to fabricate microstructures such as diaphragms and cantilevers on a silicon wafer.
- It is also used to create more complicated 3-D microstructures on a silicon chip for applications such as ink-jet printing devices and microfluidic systems

Challenges with anisotropic etching

- It is slower than isotropic etching and rarely exceeds 1 $\mu\text{m}/\text{min}$.
- The etching rate is temperature sensitive.
- Usually requires an elevated temperature of 100 °C in the process which precludes the use of many photoresistive masking materials.

It is used to create precise shapes like sharp corners, flat surfaces, and deep cavities that can be easily manufactured using this anisotropic etching process. These anisotropic etching processes are used to fabricate microstructures such as diaphragms and cantilevers on a silicon wafer. They are also efficiently used to create more complicated 3D microstructures on a silicon chip for applications such as inkjet printing devices and microfluidic systems. The key challenges with anisotropic etching are that it is slower than isotropic etching and it rarely exceeds one micrometer per minute; it's a kind of stage-by-stage process evolved for etching the surface in a particular direction. Etching rate is highly temperature sensitive and usually requires an elevated temperature of 100 degrees Celsius in the process, which precludes the use of many photoresistive masking materials.

This is one of the major challenges of opting for anisotropic etching. The dry etching involves the removal of the substrate material by a gaseous etchant without the use of any chemicals or rinsing. For the parts which require some maximum precision and more

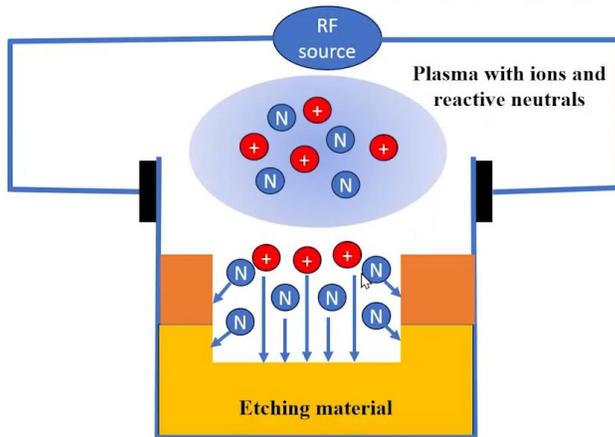
control of the shape of the etch geometry, the dry etching method is considered to be the preferred option. In this dry etching method, a substrate is loaded into a sealed process chamber to produce a plasma under a vacuum of a special process gas. From this plasma, reactive species are created, allowing for chemical or physical interaction with the substrate.

Dry Etching

- Dry etching involves the removal of substrate materials by gaseous etchants without any use of chemicals or rinsing.
- For Parts requiring maximum precision, and more control of the shape of the etched geometry, dry etching method is a preferred option.
- A substrate is loaded in a sealed process chamber to produce a plasma under a vacuum of special process gases. From this plasma, reactive species are created allowing for chemical or physical interactions with the substrate.
- These obtained species either interact in a chemical manner (reaction with a surface atom) or physical manner (collision with a surface atom) to remove material from the substrate surface.
- Herein, atom layer by atom layer is removed to ensure a highly controlled etch process. For an even more selective removal of material, dry etching is traditionally combined with photolithography processing.
- The complex combination of variables in the process chamber allows for steering to process to maximum precision.

These obtained species either interact in a chemical manner, react with the surface atom, or interact in a physical manner, colliding with the surface atom to remove the material from the substrate surfaces. Herein, an atomic layer by atomic layer is removed to ensure a highly controlled etch process. For an even more selective removal of material, dry etching is traditionally combined with a photolithography process. These kinds of complex combinations of variables in the process chamber allow for steering the process with maximum precision mechanisms, which is considered to be one of the major advantages of the methodology for a dry etching process. So in the case of a dry etching process, consider the simple plasma-based process.

Plasma Ion Etching



- The process involves adding a chemically reactive gas such as CCl_2F_2 to plasma that contains ions and has its own carrier gas (argon).
- The reactive gas produces reactive neutrals when it is ionized in the plasma.
- The reactive neutral bombards the target on both the sidewalls as well as normal surface whereas the charged ions bombard only the normal surface of the substrate.
- Etching of the substrate material is accomplished by high-energy ions in the plasma bombarding the substrate surface with simultaneous chemical reaction between reactive neutral ions and substrate material.
- This high energy reaction causes local evaporation and thus results in the removal of substrate material.
- **Note:** The etching front moves more rapidly in the depth direction than in the direction of sidewalls. This is due to larger number of high-energy particles involving both the neutral ions and charged ions bombarding the normal surface while the side walls are bombarded by neutral ions only.

This process involves adding chemically reactive gases such as CCl_2F_2 to plasma that contains ions and has its own carrier gas (argon). When looking into the overall configuration of plasma ion etching, there is an etching material that is available, and then there is a plasma with ions that react with the neutral material. So the reactive gas produces a reactive neutral when it is ionized in the plasma. These reactive neutrals bombard the target on both the side walls as well as the normal surfaces, whereas the charged ions bombard only the normal surfaces of the substrate. The etching of the substrate material is accomplished by high-energy ions and the plasma bombarding the substrate.

Plasma Ion Etching

- Conventional dry etching is a very slow process, at a rate of about $0.1 \mu\text{m}/\text{min}$ or $100 \text{ \AA}/\text{min}$ whereas plasma ion etching can increase the etching rates in the order of $2000 \text{ \AA}/\text{min}$.
- The increase in etching rate is primarily due to increased mean free path of the reacting gas molecules in the depth to be etched.
- Plasma ion etching of silicon substrates is typically faster and cleaner over wet etching. A typical dry etching rate is $5 \mu\text{m}/\text{min}$ which is about 5 times that of wet etching.

Challenges

- It is also limited to producing shallow trenches as in wet etching process.
- The process of dry etching is limited to producing MEMS with low aspect ratios. (Aspect ratio= dimension/ depth)
- For plasma ion etching, the aspect ratio is less than 15.
- **Contamination of substrate surface by residues is another challenge.**

Surface with simultaneous chemical reactions between reactive neutral ions and the substrate material exhibits. This high-energy reaction causes local evaporation, thus

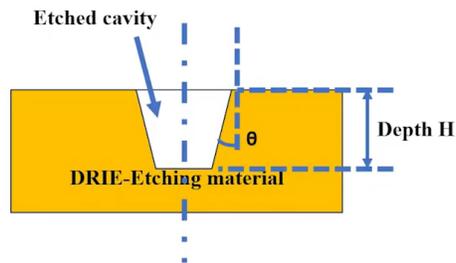
resulting in the removal of the substrate material. One of the key points that may need to be considered here is that the etching front moves more rapidly in the depth direction than in the direction of the side walls. This is due to a large number of high-energy particles involving both the neutral ions and the charged ions bombarding the normal surface, while the side walls are bombarded by the neutral ions only. This is the overall characteristic of plasma ion etching.

The plasma ion etching is a very slow process; it is at the rate of 0.1 micrometer per minute or 100 angstroms per minute, and the plasma ion etching can increase the etching rate to the order of 2000 angstroms per minute. The increase in the etching is primarily due to an increase in the mean free path of reactant gas molecules in the depth to be etched. In the case of plasma ion etching, a silicon substrate is typically faster and cleaner than wet etching. A typical dry etching rate is 5 micrometers per minute, which is about 5 times that of the wet etching process.

Deep reactive Ion Etching

Why is DRIE required?

- Despite significant increase in etching rate and depth of etched trench or cavity that can be achieved with plasma, the etched walls in the trench remains at wide angle (θ) to its depth.
- This cavity angle (θ) is very critical in MEMS structures and has to be $\sim 0^\circ$ especially comb electrodes in microgrippers where the faces of the electrodes must be parallel to each other.

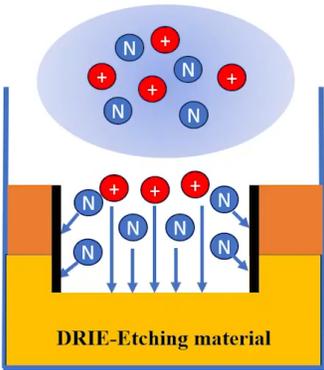


Some of the key challenges that need to be addressed are that it is also limited to producing shallow trenches, as in the case of a wet etching process. This is because the plasma will try to disperse in different directions, and this may result in a certain amount of distractions at the end of the curvature of these particular structures. Second, the process of dry etching is limited in producing MEMS with a low aspect ratio (aspect ratio is dimension per depth). For plasma ion etching, the aspect ratio is less than 15. The contamination of the substrate surface by residue is another challenge that occurs in the case of the plasma ion etching process.

The deep reactive ion etching, also called DRIE, is the process that has a significant increase in the etching rate and depth of the etched trench or cavity that can be achieved

with the plasma; the etched wall in the trench remains at a wide-angle theta at its depth. So, the cavity angle theta is very crucial in MEMS structures and has to be at 0 degrees, especially when comb electrodes and micro grippers are involved, where the faces of the electrodes must be parallel to each other. In that particular aspect, such a kind of DRE can be efficiently deployed. The deep reactive ion etching process produces a thin film protective of a few microns on the side walls during the etching process. It involves the use of a high-density plasma source that allows an alternative process of plasma etching of substrate material and deposition of etching protective material along the sidewalls.

Deep reactive Ion Etching



- The DRIE process produces thin protective films of few microns on sidewalls during etching process.
- Involves use of high-density plasma source that allows alternating processes of plasma etching of substrate material and deposition of etching protective material on the sidewalls.
- These etching protective materials (black in image) are materials with high selectivity ratio such as silicon di-oxide. Polymers and photoresists are used as protective material.
- The working principle is similar to plasma ion etching process.
- The process effectively increased the aspect ratio from 15 to 30 with currently report suggests of aspect ratio 100 and above.

These etching protective materials are materials with a high selectivity ratio, such as silicon dioxide, polymers, and photoresist, that are used as protective materials. The working principle of deep reactive ion etching is almost similar to plasma ion etching, so the process effectively increases the aspect ratio from 15 to 30, with current reports suggesting it has an aspect ratio of 100 and above. While comparing the dry etching process and wet etching process with reference to directionality, the dry etching is good for most materials; however, in wet etching, only single materials with a particular aspect ratio can be deployed. According to process automation, the dry etching process is good; however, in the wet etching process, it is very difficult to deploy process automation. Based on the selectivity perspective point of view, dry etching is almost poor; however, in wet etching, its characteristics are quite good.

From an environmental impact perspective, there are not many residues observed in the case of a dry etching process. In the case of a wet etching process, there is always a kind of residue left behind, which may have an impact on the environmental aspect. Then, as far as masking film adherence is concerned, in a dry etching process, it is not as critical; however, in a wet etching process, it is highly critical. Now, the materials that need to be etched include specific materials that can only be etched using the dry etching

process. In contrast, the wet etching process has the capability to work with all kinds of materials.

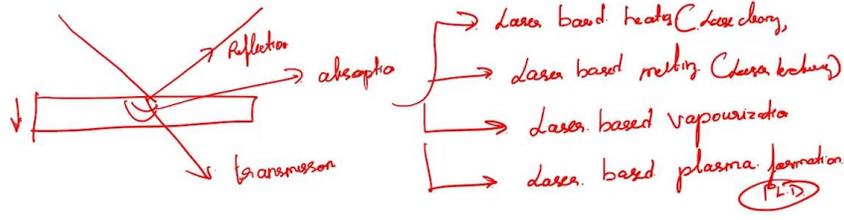
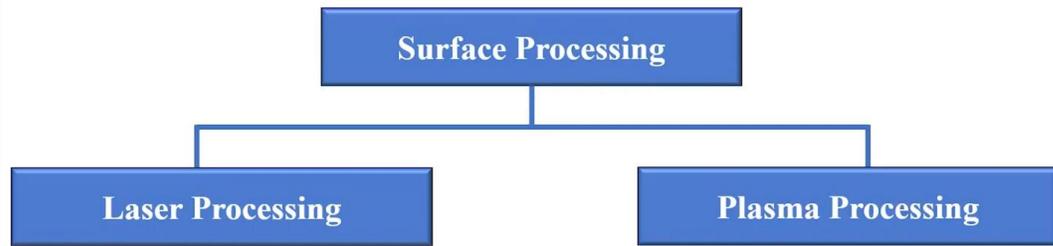
Dry vs Wet Etching		
Parameters	Dry etching	Wet etching
Directionality	Good for most materials	Only with single-crystal materials (aspect ratio upto 100)
Production-automation	Good	Poor
Selectivity	Poor	Very Good
Environmental Impact	Low	High
Masking film adherence	Not as critical	Very critical
Materials to be etched	Specific materials	All
Process scale up	Difficult	easy
Cleanliness	Conditionally clean	Good to very good
Critical dimensional control	Very good (<0.1 μm)	Poor
Equipment cost	Expensive	Less expensive
Typical etch rate	Slow (0.1 $\mu\text{m}/\text{min}$) to fast (6 $\mu\text{m}/\text{min}$)	Fast (1 $\mu\text{m}/\text{min}$ and up)
Operational Parameters	Many	Few
Control of etch rate	Good in case of slow etch	Difficult

For example, in the case of a dry etching process, if we are using a kind of brittle material, it may result in multiple cracks in this material. So, this is one important aspect that may affect the overall performance when trying to use a dry etching process for a brittle material. Then, with reference to process scale-up, the dry etching process is difficult, while the wet etching process is quite easy. From a cleanliness perspective, it is conditionally clean, while from a wet etching point of view, it is good to very good. Critical dimensional control is concerned; it is very good in dry etching.

It is less than 0.1 micron, which is highly used in micro robotics. In the case of the wet etching process, this parameter is considered to be pretty poor. From a cost-wise perspective, the dry etching process is slightly more costly compared to the wet etching process. In the case of the dry etching process, a different kind of sub-integration needs to be included, which makes the system more costly. In the case of the wet etching process, it is a bit less expensive because it has more to do with chemical interactions with the material.

As etch rate is considered, the dry etching process is slow. It is on the order of 0.1 micrometer per minute with a range of six micrometers per minute. However, in the wet etching process, it is in the range of one micrometer per minute and up, which is slightly faster. From an operational parameters point of view, in the dry etching process, many parameters are involved in the process, while in the wet etching process, it is very limited to only a few characteristics.

Surface Processing



Control of each rate is concerned so good in the case of slow etch; however, it is difficult in the case of a wet etching process. Now, with reference to patterning, surface generation, or functionalizing perspectives, surface processing plays a vital role. As far as this surface processing is concerned, it has nothing to do with adding or dropping the material. It has more to do with functionalizing the surface based on the requirement. From the perspective of micro robotic applications, two different surface processing techniques are being used efficiently. One is called a laser processing technique, and the other is called a plasma processing technique. The laser processing technique is concerned; first, let us consider a material. When the light falls on a material, it exhibits three different phenomena: reflection, absorption, and transmission. From a reflective perspective, let us take a simple mirror; when the laser hits this mirror, we will have a reflection that is exhibited here. From a transmission perspective, a certain amount of mirrors are a bit transparent enough so that when the light falls on them, it tries to transmit to the system.

From an absorption perspective, when the light hits the surface, the material will try to absorb the laser light, resulting in a kind of heat transfer, as exhibited here. This is a mechanism that occurs when the laser interacts with the material. The fundamentals of laser processing can be classified as laser-based heating, where a certain amount of heat is generated on the surface to create some kind of microstructures or to functionalize the structures based on the requirements. Apart from that, others are laser-based melting, laser-based vaporization, and laser-based plasma formation. PLD is a very good example of laser-based plasma formation.

Laser Processing

- Laser processing has emerged as a highly effective technique for fabricating hydrophobic and superhydrophobic surfaces, particularly for microrobots that operate in aqueous or humid environments.
- **These surfaces help in reducing drag, improving mobility, and preventing contamination.**
- **The process leverages laser-material interactions to create micro/nanostructures that enhance water repellency.**



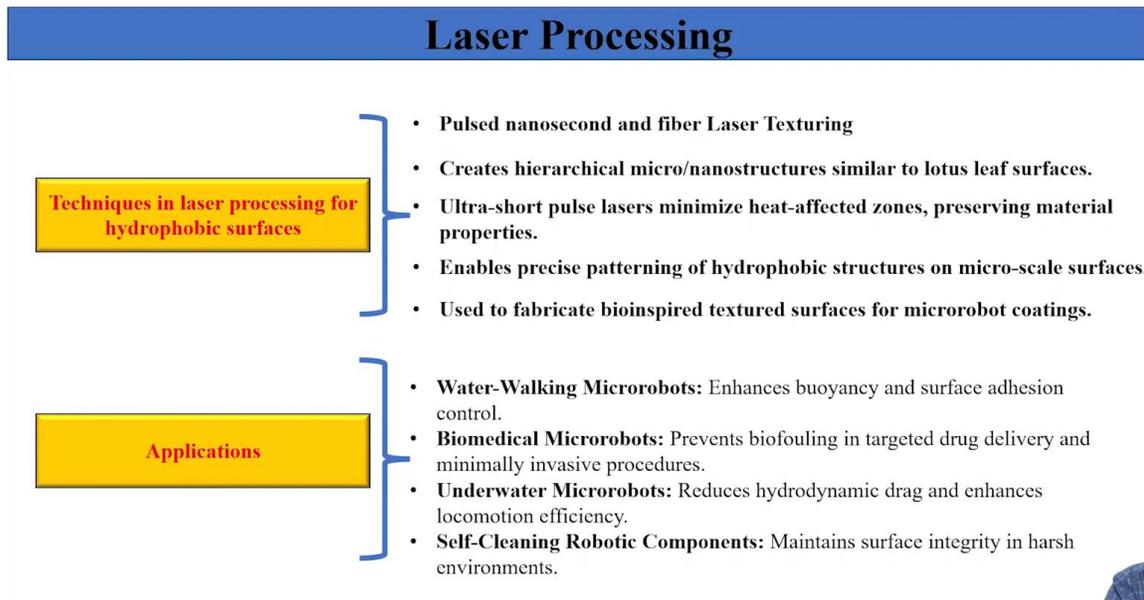
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As far as laser-based heating is concerned, we can have a laser cleaning process, a laser-based functionalization process, laser texturing, etc., which come under this particular category. Some important applications where a laser is used for functionalizing the surface for microrobotic applications. Laser processing is a highly effective technique for fabricating hydrophobic and superhydrophobic surfaces, particularly micro robots that operate in aqueous environments or in a humid environment. These surfaces help in reducing the drag, they also improve mobility, and they also prevent contamination.

As discussed in our first module about its applications in micro robotic applications, we noted that this kind of micro robot is efficiently used for surveillance applications or to understand pollutants, etc. There are also different microbiome-mimicking robots being developed by various research groups, which have been functionalized in such a way that they have a hydrophobic surface. Through these hydrophobic surfaces, water contamination can result in enhanced water repellency. So, here, in order to have a better understanding, we need to have an understanding of the laser material interaction and create micro and nano structures to enhance the processing. In laser processing, this particular course focuses solely on the generation of hydrophobic surfaces.

So, the technique in laser processing for hydrophobic surfaces is concerned, deploying a kind of pulsed nano or nanosecond laser or a fiber laser for texturing on the surface. It can also create hierarchical micro and nano structures similar to a lotus leaf structure. Ultra-short pulse laser, which minimizes the heat-affected zone, can be used for preserving the material properties. It also enables precise patterning of hydrophobic structures on microscale surfaces, and it is also used to fabricate bio-inspired textured surfaces for microrobot coating. With reference to the application point of view, micro robotic striders are a kind of water-walking microrobots.

In these robots, the major requirement is that they should have enhanced buoyancy and good surface adhesion control. Further in the biomedical microrobots application, one of the important aspects that may need to be considered is that they should prevent biofouling in targeted drug delivery as well as in the case of minimally invasive procedures. Therefore, by having appropriate surface structures, they can prevent biofouling-related issues. Now, with reference to the underwater microrobots' point of view, it reduces hydrodynamic drag and enhances locomotion efficiency. So this is one important aspect that is being considered in the case of microrobotic applications, especially when we were discussing the scaling loss with reference to fluid interaction.



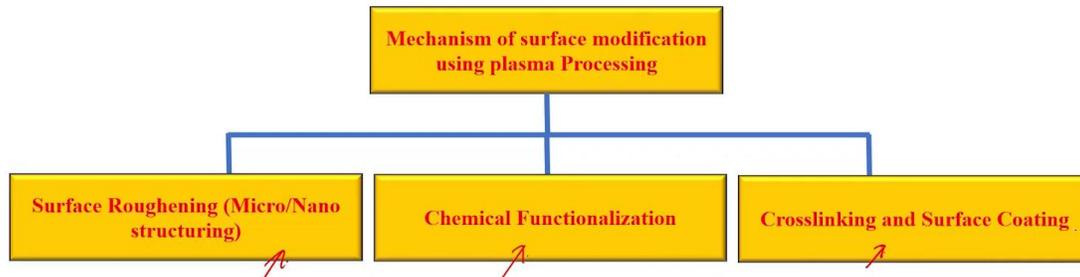
Therefore, the movement of the fluid needs to be appropriately taken into account in such a way that the surfaces being generated will help ensure smooth locomotion of these microrobotic structures in functional applications. Next is a self-healing robotic component. So, as we try to go on a micro scale, this self-healing plays a vital role. Because if the surface of these microrobots has the capability to attract a certain amount of particles, it may result in some kind of undulated behavior in these structures. In order to avoid that, these robots have a kind of self-cleaning behavior; sometimes it is through coatings or through textures, so that we can maintain a kind of surface integrity in the case of a harsh environment.

Now, as far as these structures are concerned, this is one demo that I would like to show from our lab, where we have created a certain amount of patterns. In these patterns, if you see, we have used a kind of NDAG laser; basically, it's a kind of continuous laser that we have used, and these lasers are integrated with the galvano. The overall wavelength of this laser is close to around 1064 nanometers, and these are some kinds of patterns that can be generated from it. This is a kind of laser that is used for scanning the

surface; appropriate scanning will be helpful for us to create textures. The overall manipulation of these structures is generated using a galvanometer, which is capable enough of creating a textured pattern on the surface.

Plasma Processing

Plasma treatment is a powerful surface modification technique used to tailor the wettability of polymers, enabling the transformation from hydrophilic to hydrophobic states. This process is particularly beneficial in applications such as biomedical devices, coatings for microrobots, and microfluidic systems.



These textures are efficient enough that they take care of hydrophobicity, biofouling-related characteristics, and the overall functionality, which will enhance the propulsion of the system. In the plasma processing technique, there is a plasma chamber; plasma is generated by applying a bias between two different leads. So, when a bias is employed between these two leads, plasma is generated from it. The plasma is a kind of cloud of dense material, which will be helpful for us to change the surface properties of the material based on the requirements or based on the characteristics. The one good example where "had" is used is a small PTFE base structure.

In this PTFE base structure, there is a kind of plasma treatment that is being deployed on it. Through this plasma treatment, the structures were appropriately manipulated, and these manipulated structures have the capability to have different functionality; they have control over the hydrophobic as well as the hydrophilic transformation based on our requirements. The mechanism of this plasma processing is a powerful surface modification technique that is used to tailor the wettability of polymers and enables the transformation from a hydrophilic to a hydrophobic state. This process is particularly beneficial in applications such as biomedical devices, coatings for micro robots, and microfluidic systems. These mechanisms of surface modification using this plasma processing are classified under three different categories.

One is towards surface roughening, which is towards micro and nano structuring. Second is towards the chemical functionalization so that in certain applications, we try to change the overall characteristics of the bond structure. By changing the characteristics of the bond structure, we can functionalize the structure. Then one of the important functionalities is with reference to cross-linking and surface coating, which is possible by inducing a certain amount of gaseous regions in the plasma process. So that these gaseous

regions are capable enough in such a way that they will try to realize the process and these realized processes will take care of the overall functionality of the requirement.