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Deposition Processes

MEMS Thin Film Deposition Processes

One of the basic building blocks in MEMS processing is the ability to deposit thin films of material. In this text we assume a thin film to have a thickness anywhere between a few nanometers to about 100 micrometer. The film can subsequently be locally etched using processes such as [Lithography](#) and [Etching](#) (see page 10).

MEMS deposition technology can be classified in two groups:

1. Depositions that happen because of a **chemical** reaction:
 - **C**hemical **V**apor **D**eposition (CVD)
 - Electrodeposition
 - Epitaxy
 - Thermal oxidation

These processes exploit the creation of solid materials directly from chemical reactions in gas and/or liquid compositions or with the substrate material. The solid material is usually not the only product formed by the reaction. Byproducts can include gases, liquids and even other solids.

2. Depositions that happen because of a **physical** reaction:
 - **P**hysical **V**apor **D**eposition (PVD)
 - Casting

Common for all these processes are that the material deposited is physically moved on to the substrate. In other words, there is no chemical reaction which forms the material on the substrate. This is not completely correct for casting processes, though it is more convenient to think of them that way.

This is by no means an exhaustive list since technologies evolve continuously.

Chemical Vapor Deposition (CVD)

In this process, the substrate is placed inside a reactor to which a number of gases are supplied. The fundamental principle of the process is that a chemical reaction takes place between the source gases. The product of that reaction is a solid material with condenses on all surfaces inside the reactor.

The two most important CVD technologies in MEMS are the **L**ow **P**ressure CVD (LPCVD) and **P**lasma **E**nhanced CVD (PECVD). The LPCVD process produces layers with excellent uniformity of thickness and material characteristics. The main problems with the process are the high deposition temperature (higher than 600°C) and the relatively slow deposition rate. The PECVD process can operate at lower temperatures (down to 300° C) thanks to the extra energy supplied to the gas molecules by the plasma in the reactor. However, the quality of the films tend to be inferior to processes running at higher temperatures. Secondly, most PECVD deposition systems can only deposit the material on one side of the wafers on 1 to 4 wafers at a time. LPCVD systems deposit films on both sides of at least 25 wafers at a time. A schematic diagram of a typical LPCVD reactor is shown in the figure below.

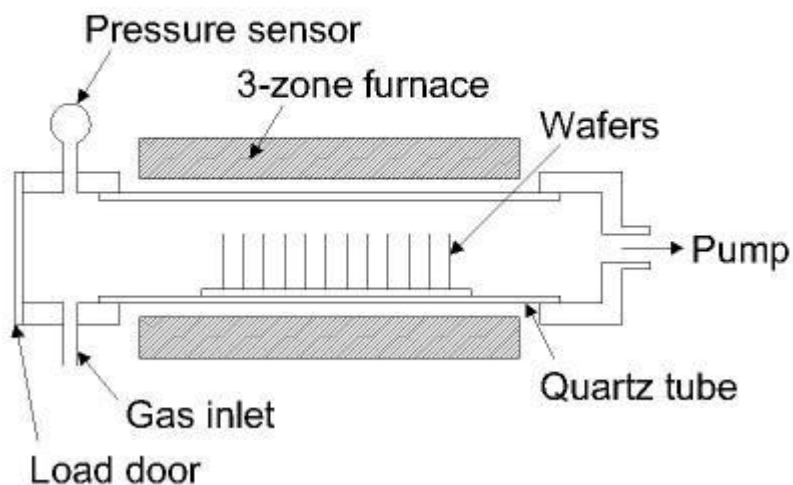


Figure 1: Typical hot-wall LPCVD reactor.

When do I want to use CVD?

CVD processes are ideal to use when you want a thin film with good step coverage. A variety of materials can be deposited with this technology, however, some of them are less popular with fabs because of hazardous byproducts formed during processing. The quality of the material varies from process to process, however a good rule of thumb is that higher process temperature yields a material with higher quality and less defects.

Electrodeposition

This process is also known as "electroplating" and is typically restricted to electrically conductive materials. There are basically two technologies for plating: Electroplating and Electroless plating. In the electroplating process the substrate is placed in a liquid solution (electrolyte). When an electrical potential is applied between a conducting area on the substrate and a counter electrode (usually platinum) in the liquid, a chemical redox process takes place resulting in the formation of a layer of material on the substrate and usually some gas generation at the counter electrode.

In the electroless plating process a more complex chemical solution is used, in which deposition happens spontaneously on any surface which forms a sufficiently high electrochemical potential with the solution. This process is desirable since it does not require any external electrical potential and contact to the substrate during processing. Unfortunately, it is also more difficult to control with regards to film thickness and uniformity. A schematic diagram of a typical setup for electroplating is shown in the figure below.

When do I want to use electrodeposition?

The electrodeposition process is well suited to make films of metals such as copper, gold and nickel. The films can be made in any thickness from $\sim 1\mu\text{m}$ to $>100\mu\text{m}$. The deposition is best controlled when used with an external electrical potential, however, it requires electrical contact to the substrate when immersed in the liquid bath. In any process, the surface of the substrate must have an electrically conducting coating before the deposition can be done.

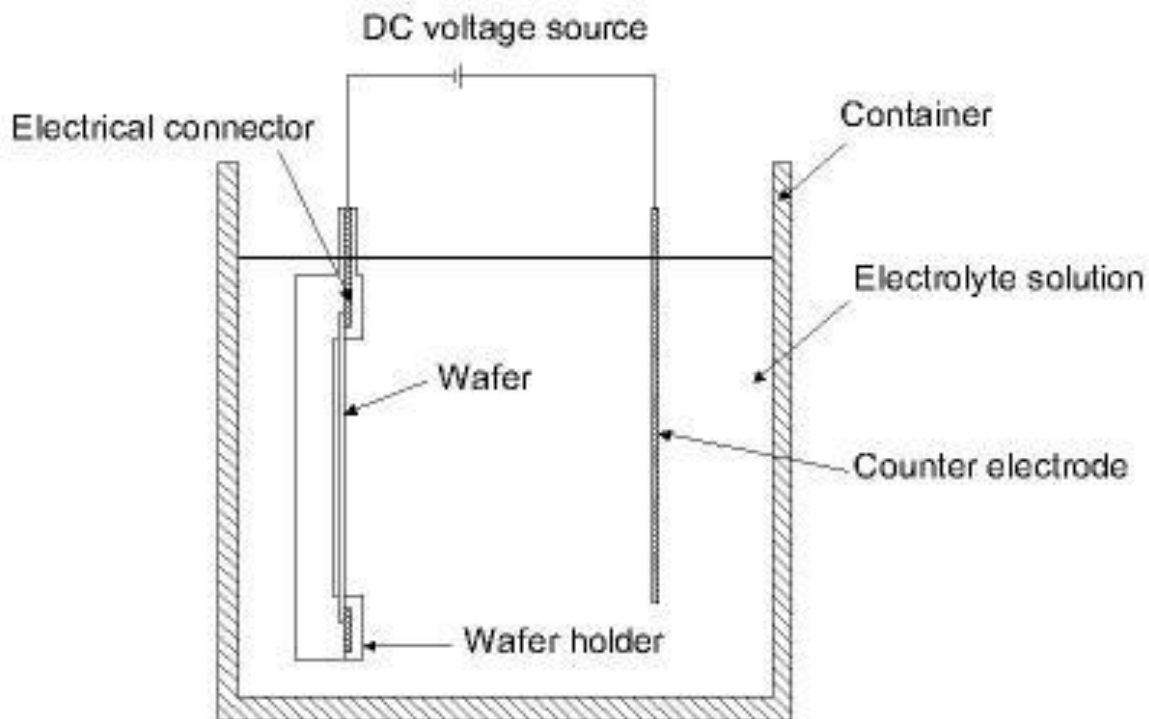


Figure 2: *Typical setup for electrodeposition.*

Epitaxy

This technology is quite similar to what happens in CVD processes, however, if the substrate is an ordered semiconductor crystal (i.e. silicon, gallium arsenide), it is possible with this process to continue building on the substrate with the same crystallographic orientation with the substrate acting as a seed for the deposition. If an amorphous/polycrystalline substrate surface is used, the film will also be amorphous or polycrystalline.

There are several technologies for creating the conditions inside a reactor needed to support epitaxial growth, of which the most important is **V**apor **P**hase **E**pitaxy (VPE). In this process, a number of gases are introduced in an induction heated reactor where only the substrate is heated. The temperature of the substrate typically must be at least 50% of the melting point of the material to be deposited.

An advantage of epitaxy is the high growth rate of material, which allows the formation of films with considerable thickness ($>100\mu\text{m}$). Epitaxy is a widely used technology for producing silicon on insulator (SOI) substrates. The

technology is primarily used for deposition of silicon. A schematic diagram of a typical vapor phase epitaxial reactor is shown in the figure below.

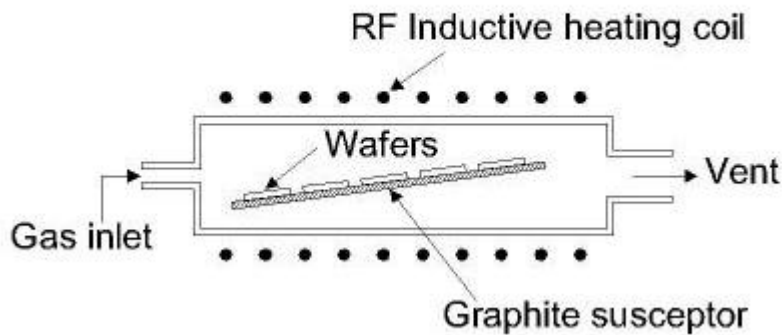


Figure 3: *Typical cold-wall vapor phase epitaxial reactor.*

When do I want to use epitaxy?

This has been and continues to be an emerging process technology in MEMS. The process can be used to form films of silicon with thicknesses of $\sim 1\mu\text{m}$ to $>100\mu\text{m}$. Some processes require high temperature exposure of the substrate, whereas others do not require significant heating of the substrate. Some processes can even be used to perform selective deposition, depending on the surface of the substrate.

Thermal oxidation

This is one of the most basic deposition technologies. It is simply oxidation of the substrate surface in an oxygen rich atmosphere. The temperature is raised to 800°C - 1100°C to speed up the process. This is also the only deposition technology which actually consumes some of the substrate as it proceeds. The growth of the film is spurred by diffusion of oxygen into the substrate, which means the film growth is actually downwards into the substrate. As the thickness of the oxidized layer increases, the diffusion of oxygen to the substrate becomes more difficult leading to a parabolic relationship between film thickness and oxidation time for films thicker than $\sim 100\text{nm}$. This process is naturally limited to materials that can be oxidized, and it can only form films that are oxides of that material. This is the classical process used to form silicon dioxide on a silicon substrate. A schematic diagram of a typical wafer oxidation furnace is shown in the figure below.

When do I want to use thermal oxidation?

Whenever you can! This is a simple process, which unfortunately produces films with somewhat limited use in MEMS components. It is typically used to form films that are used for electrical insulation or that are used for other process purposes later in a process sequence.

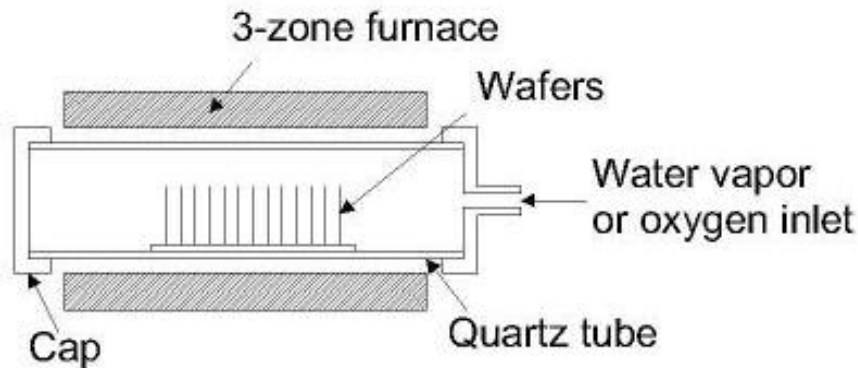


Figure 4: *Typical wafer oxidation furnace.*

Physical Vapor Deposition (PVD)

PVD covers a number of deposition technologies in which material is released from a source and transferred to the substrate. The two most important technologies are evaporation and sputtering.

When do I want to use PVD?

PVD comprises the standard technologies for deposition of metals. It is far more common than CVD for metals since it can be performed at lower process risk and cheaper in regards to materials cost. The quality of the films are inferior to CVD, which for metals means higher resistivity and for insulators more defects and traps. The step coverage is also not as good as CVD.

The choice of deposition method (i.e. evaporation vs. sputtering) may in many cases be arbitrary, and may depend more on what technology is available for the specific material at the time.

Evaporation

In evaporation the substrate is placed inside a vacuum chamber, in which a block (source) of the material to be deposited is also located. The source material is then heated to the point where it starts to boil and evaporate. The vacuum is required to allow the molecules to evaporate freely in the

chamber, and they subsequently condense on all surfaces. This principle is the same for all evaporation technologies, only the method used to the heat (evaporate) the source material differs. There are two popular evaporation technologies, which are e-beam evaporation and resistive evaporation each referring to the heating method. In e-beam evaporation, an electron beam is aimed at the source material causing local heating and evaporation. In resistive evaporation, a tungsten boat, containing the source material, is heated electrically with a high current to make the material evaporate. Many materials are restrictive in terms of what evaporation method can be used (i.e. aluminum is quite difficult to evaporate using resistive heating), which typically relates to the phase transition properties of that material. A schematic diagram of a typical system for e-beam evaporation is shown in the figure below.

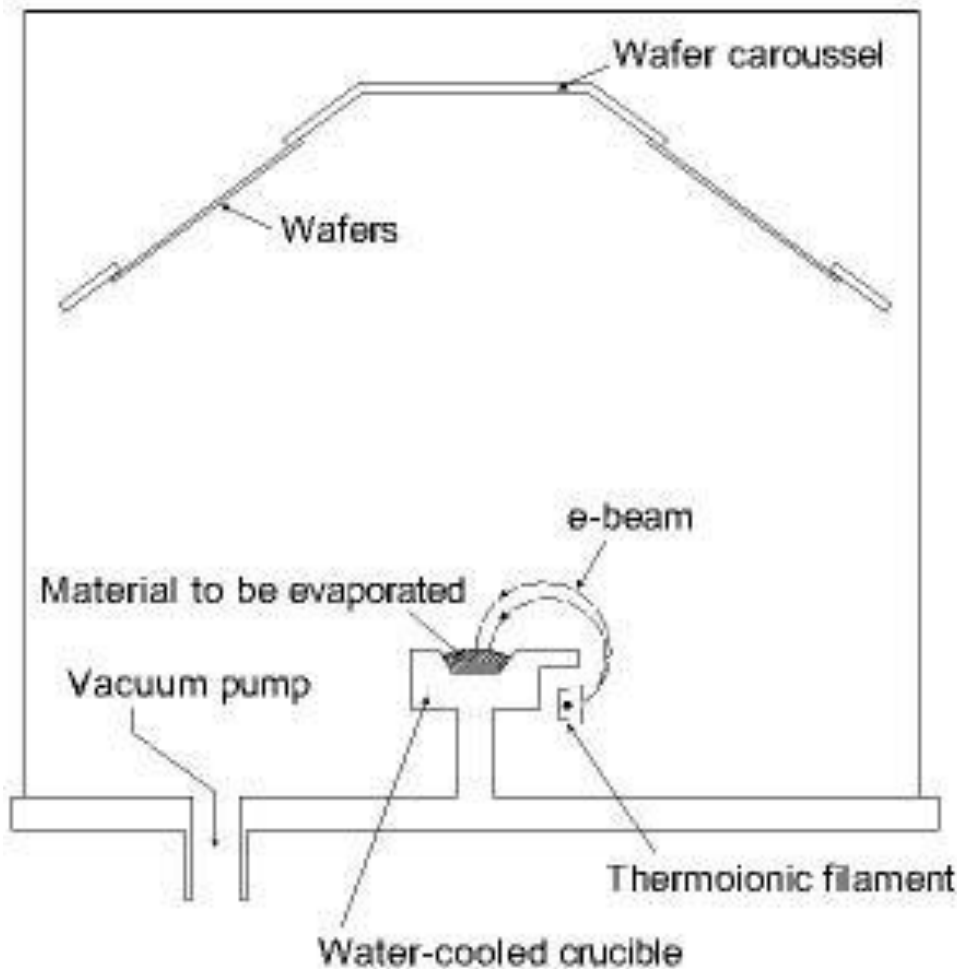


Figure 5: Typical system for e-beam evaporation of materials.

Sputtering

Sputtering is a technology in which the material is released from the source at much lower temperature than evaporation. The substrate is placed in a vacuum chamber with the source material, named a target, and an inert gas (such as argon) is introduced at low pressure. A gas plasma is struck using an RF power source, causing the gas to become ionized. The ions are accelerated towards the surface of the target, causing atoms of the source material to break off from the target in vapor form and condense on all surfaces including the substrate. As for evaporation, the basic principle of sputtering is the same for all sputtering technologies. The differences typically relate to the manner in which the ion bombardment of the target is realized. A schematic diagram of a typical RF sputtering system is shown in the figure below.

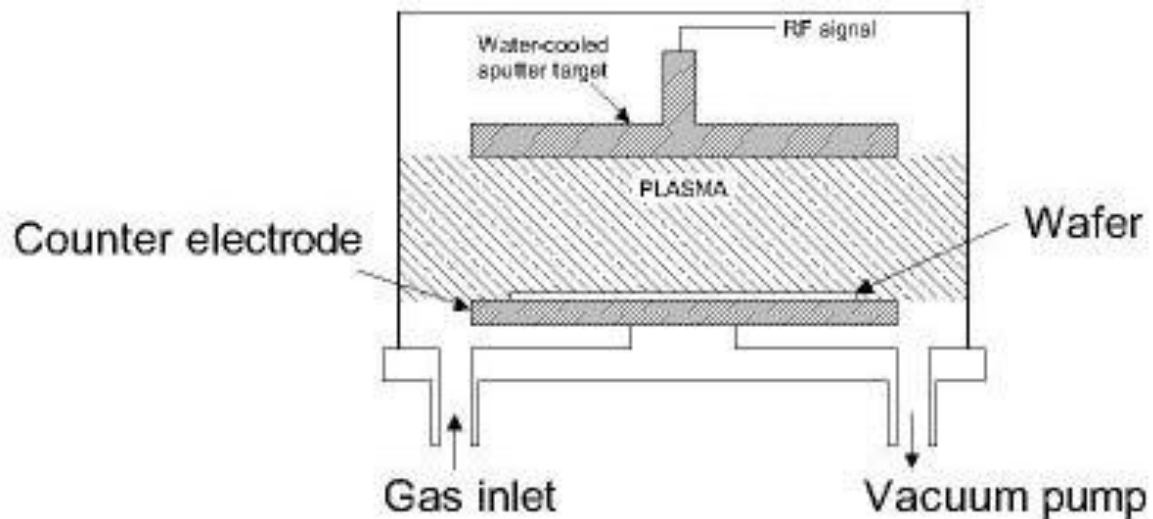


Figure 6: *Typical RF sputtering system.*

Casting

In this process the material to be deposited is dissolved in liquid form in a solvent. The material can be applied to the substrate by spraying or spinning. Once the solvent is evaporated, a thin film of the material remains on the substrate. This is particularly useful for polymer materials, which may be easily dissolved in organic solvents, and it is the common method used to apply photoresist to substrates (in photolithography). The thicknesses that can be cast on a substrate range all the way from a single monolayer of

molecules (adhesion promotion) to tens of micrometers. In recent years, the casting technology has also been applied to form films of glass materials on substrates. The spin casting process is illustrated in the figure below.

When do I want to use casting?

Casting is a simple technology which can be used for a variety of materials (mostly polymers). The control on film thickness depends on exact conditions, but can be sustained within +/-10% in a wide range. If you are planning to use photolithography you will be using casting, which is an integral part of that technology. There are also other interesting materials such as polyimide and spin-on glass which can be applied by casting.

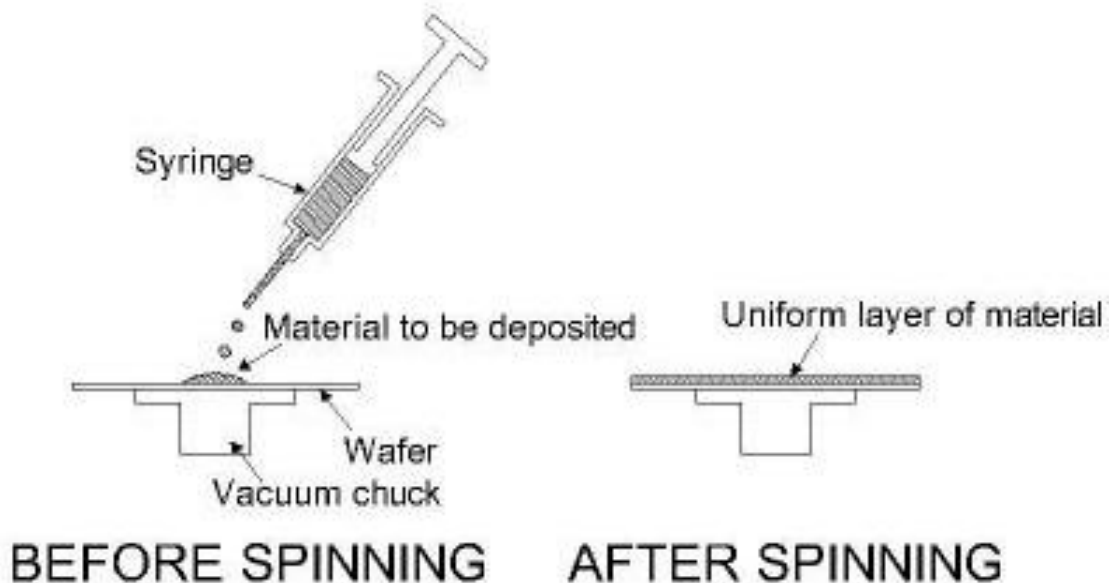


Figure 7: *The spin casting process as used for photoresist in photolithography.*

Etching Processes

In order to form a functional MEMS structure on a substrate, it is necessary to etch the thin films previously deposited and/or the substrate itself. In general, there are two classes of etching processes:

1. Wet etching where the material is dissolved when immersed in a chemical solution
2. Dry etching where the material is sputtered or dissolved using reactive ions or a vapor phase etchant

In the following, we will briefly discuss the most popular technologies for wet and dry etching.

Wet etching

This is the simplest etching technology. All it requires is a container with a liquid solution that will dissolve the material in question. Unfortunately, there are complications since usually a mask is desired to selectively etch the material. One must find a mask that will not dissolve or at least etches much slower than the material to be patterned. Secondly, some single crystal materials, such as silicon, exhibit anisotropic etching in certain chemicals. Anisotropic etching in contrast to isotropic etching means different etch rates in different directions in the material. The classic example of this is the $\langle 111 \rangle$ crystal plane sidewalls that appear when etching a hole in a $\langle 100 \rangle$ silicon wafer in a chemical such as potassium hydroxide (KOH). The result is a pyramid shaped hole instead of a hole with rounded sidewalls with a isotropic etchant. The principle of anisotropic and isotropic wet etching is illustrated in the figure below.

When do I want to use wet etching?

This is a simple technology, which will give good results if you can find the combination of etchant and mask material to suit your application. Wet etching works very well for etching thin films on substrates, and can also be used to etch the substrate itself. The problem with substrate etching is that isotropic processes will cause undercutting of the mask layer by the same distance as the etch depth. Anisotropic processes allow the etching to stop on certain crystal planes in the substrate, but still results in a loss of space, since these planes cannot be vertical to the surface when etching holes or cavities. If this is a limitation for you, you should consider dry etching of the substrate instead. However, keep in mind that the cost per wafer will be 1-2 orders of magnitude higher to perform the dry etching

If you are making very small features in thin films (comparable to the film thickness), you may also encounter problems with isotropic wet etching, since the undercutting will be at least equal to the film thickness. With dry etching it is possible to etch almost straight down without undercutting, which provides much higher resolution.

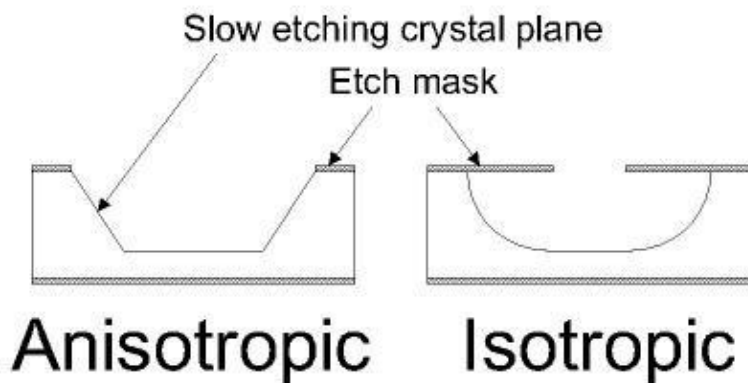


Figure 1: *Difference between anisotropic and isotropic wet etching.*

Dry etching

The dry etching technology can split in three separate classes called reactive ion etching (RIE), sputter etching, and vapor phase etching.

In RIE, the substrate is placed inside a reactor in which several gases are introduced. A plasma is struck in the gas mixture using an RF power source, breaking the gas molecules into ions. The ions are accelerated towards, and react at, the surface of the material being etched, forming another gaseous material. This is known as the chemical part of reactive ion etching. There is also a physical part which is similar in nature to the sputtering deposition process. If the ions have high enough energy, they can knock atoms out of the material to be etched without a chemical reaction. It is a very complex task to develop dry etch processes that balance chemical and physical etching, since there are many parameters to adjust. By changing the balance it is possible to influence the anisotropy of the etching, since the chemical part is isotropic and the physical part highly anisotropic the combination can form sidewalls that have shapes from rounded to vertical. A schematic of a typical reactive ion etching system is shown in the figure below.

A special subclass of RIE which continues to grow rapidly in popularity is deep RIE (DRIE). In this process, etch depths of hundreds of microns can be achieved with almost vertical sidewalls. The primary technology is based on the so-called "Bosch process", named after the German company Robert Bosch which filed the original patent, where two different gas compositions are alternated in the reactor. The first gas composition creates a polymer on the surface of the substrate, and the second gas composition etches the substrate. The polymer is immediately sputtered away by the physical part of the etching, but only on the horizontal surfaces and not the sidewalls. Since the polymer only dissolves very slowly in the chemical part of the etching, it builds up on the sidewalls and protects them from etching. As a result, etching aspect ratios of 50 to 1 can be achieved. The process can easily be used to etch completely through a silicon substrate, and etch rates are 3-4 times higher than wet etching.

Sputter etching is essentially RIE without reactive ions. The systems used are very similar in principle to sputtering deposition systems. The big difference is that substrate is now subjected to the ion bombardment instead of the material target used in sputter deposition.

Vapor phase etching is another dry etching method, which can be done with simpler equipment than what RIE requires. In this process the wafer to be etched is placed inside a chamber, in which one or more gases are introduced. The material to be etched is dissolved at the surface in a chemical reaction with the gas molecules. The two most common vapor phase etching technologies are silicon dioxide etching using hydrogen fluoride (HF) and silicon etching using xenon difluoride (XeF₂), both of which are isotropic in nature. Usually, care must be taken in the design of a vapor phase process to not have bi-products form in the chemical reaction that condense on the surface and interfere with the etching process.

When do I want to use dry etching?

The first thing you should note about this technology is that it is expensive to run compared to wet etching. If you are concerned with feature resolution in thin film structures or you need vertical sidewalls for deep etchings in the substrate, you have to consider dry etching. If you are concerned about the price of your process and device, you may want to minimize the use of dry etching. The IC industry has long since adopted dry etching to achieve small features, but in many cases feature size is not as critical in MEMS. Dry etching is an enabling technology, which comes at a sometimes high cost.

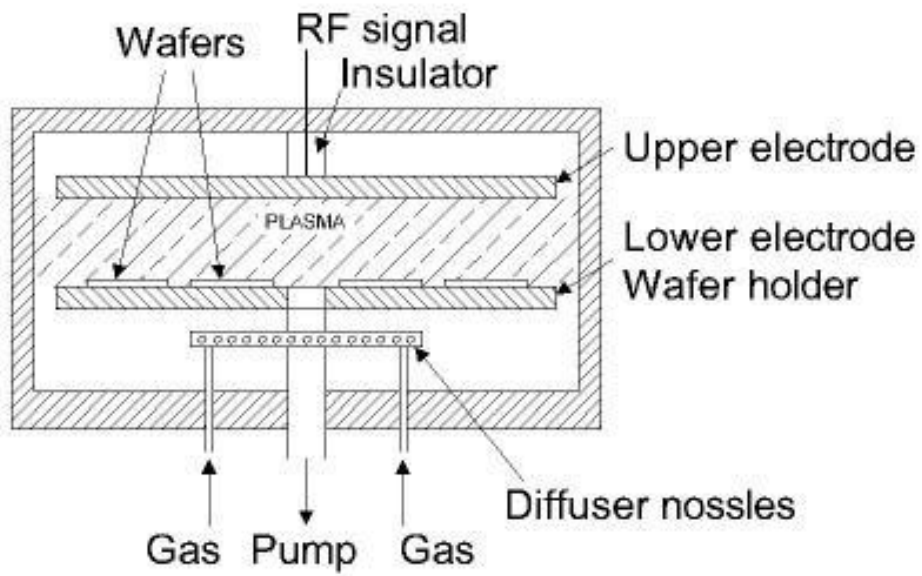


Figure 2: Typical parallel-plate reactive ion etching system.