Design Practice - 2
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Lecture - 16
Introduction to Silicon as a MEMS material

Hello and welcome to this Design Practice 2 module 16. I had discussed in great details about some of the materials which are being utilized through the routes of bulk and surface machining for realizing the MEMS structure or fabricating the MEMS structures. Today I am going to just extend this little further and just briefly summarize some of the silicon MEMS processes we had already done a review on the polymeric side, polymeric processes.

But today I am going to do more on the silicon side. So this will kind of round off you know for a designer whatever is needed as an idea who is going to come into MEMS design okay.

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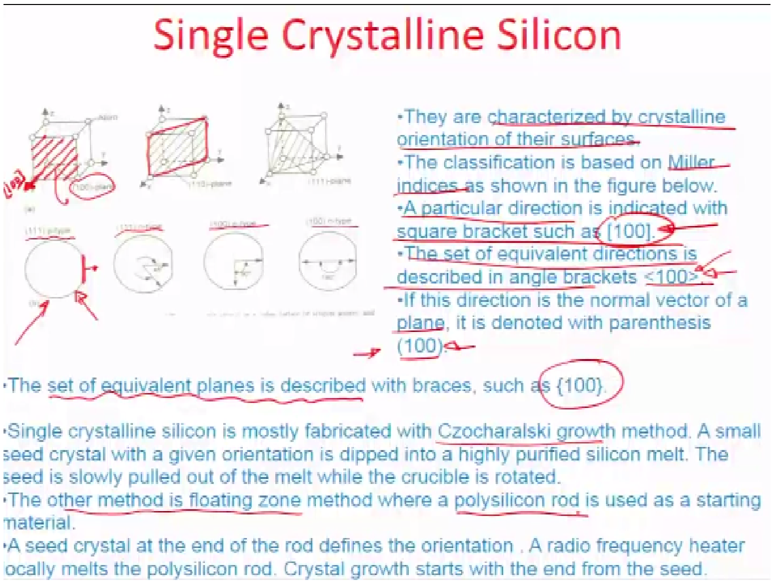

Single Crystalline Silicon

- They are characterized by crystalline orientation of their surfaces.
- The classification is based on Miller indices as shown in the figure below.
- A particular direction is indicated with square bracket such as [100].
- The set of equivalent directions is described in angle brackets <100>.
- If this direction is the normal vector of a plane, it is denoted with parenthesis (100).
- The set of equivalent planes is described with braces, such as {100}.
- Single crystalline silicon is mostly fabricated with Czocharalski growth method. A small seed crystal with a given orientation is dipped into a highly purified silicon melt. The seed is slowly pulled out of the melt while the crucible is rotated.
- The other method is floating zone method where a polysilicon rod is used as a starting material.
- A seed crystal at the end of the rod defines the orientation . A radio frequency heater locally melts the polysilicon rod. Crystal growth starts with the end from the seed.

So let us talk about first silicon and its associated materials, single crystalline silicon for example. We know that it has a cubic lattice structure and the silicon is sort of characterized by the crystalline orientation of the corresponding surfaces which are accessed in different directions. The classification is based on what we otherwise known as Miller indices and it is quite clear here shown in the figure, for example the 100 direction is corresponding to you know 1 along the x axis, 0 on the y axis and 0 on the z axis.

That means the direction which is red highlighted in this particular case. Similarly, the 110 direction is a plane indicated by this hatched area right here where there is both x and y 1 and 1 and z still being 0. So that is how the 110 direction is represented. So when we talk about directions in such a orthogonal coordinate system, the Miller indices always show the indicated direction and the indicated plane across which the perpendicular to that plane would be the indicated direction.

So a square bracket such as square bracket 100 in that case is used to represent the direction for example coming back here the direction in which this Miller index is supposed to be 100 is represented by the red arrow and this hashed plane which is there which is perpendicular to this particular direction indicated by the red arrow is actually the plane 100; so obviously the parenthesis changes.

It is basically the circular brackets which come up for representing a plane which has a primary direction 100 perpendicular to the set of plane and a set of such equivalent directions are represented by angle brackets. So basically all such directions of the type square bracket 100 come under the class of angular bracket 100 and all such planes in the direction 100 are represented through circular brackets 100.

Equivalent set of planes if supposing there are more than one such planes representing, they are represented by the third bracket 100 and so this is how conventionally the crystal direction is recorded when we talk about silicon. One has to understand very well that when we talk about MEMS processes particularly about fabricating MEMS it is important for us to understand these directions from a standpoint that tomorrow if some fabrication needs to be carried out in terms of machining, machining always happens in that direction.

So therefore obviously we need to know that very well. So typically when silicon goes out of the foundry they come as wafers and the foundry is a process where through a seed crystal you can go grow primarily in a certain direction the particular silicon. For example you can have single crystalline silicon growing all in the 100 direction. Or all in the 010 direction so on so forth.

So what it means essentially is that the seed crystal, the parent crystal which is responsible for the state change is in principle having you know a plane 100 along the direction of this plane the growth starts to happen as the seed is taken out from the melt. I am not going into the processing details of silicon because that is another topic altogether but you can have pure form of single crystalline silicon by method which is known as the Czocharalski's growth method.

So how do you know how does a person know because he is not a witness to what was the seed direction, principle seed direction. So whenever wafers are taken there is a taken out or cut or diced there is a standard norm which is followed by the industry which is about a flat which is made in the primary direction for example this 111 P type is indicated buy this flat which means this is the plane containing all the 111 plane and the direction 111 is exactly perpendicular to this particular plane.

So you have a way to represent there is an international way to depict all these different aspects in a wafer as it comes handy from the fab to the lab, from the foundry to the fab or the lab. So there are couple of other methods which are also used. Czocharalski's I already mentioned. So there is a floating zone method where you do not have any thermal gradients anymore.

So the floating zone method polysilicon material is uniformly heated through radiofrequency means so that there are no thermal gradients and so therefore float zone methods can result in even higher purity in terms of the structure etc. of the silicon.

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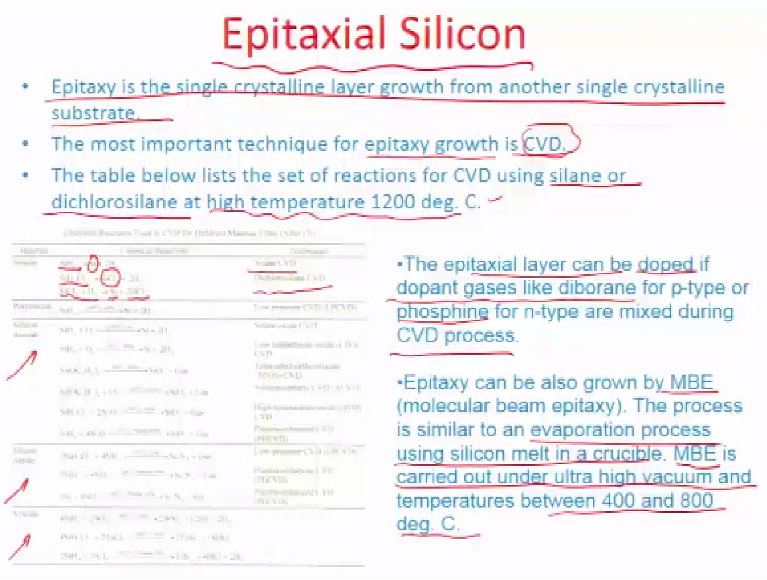

Epitaxial Silicon

- Epitaxy is the single crystalline layer growth from another single crystalline substrate.
- The most important technique for epitaxy growth is CVD.
- The table below lists the set of reactions for CVD using silane or dichlorosilane at high temperature 1200 deg. C.

•The epitaxial layer can be doped if dopant gases like diborane for p-type or phosphine for n-type are mixed during CVD process.

•Epitaxy can be also grown by MBE (molecular beam epitaxy). The process is similar to an evaporation process using silicon melt in a crucible. MBE is carried out under ultra high vacuum and temperatures between 400 and 800 deg. C.

So silicon can also be formulated through epitaxial growth or epitaxy is the single crystalline layer growth from another single crystalline substrate. It is done normally through a molecular beam which prints silicon or silicon molecules which are made to formulate the beam. The most important technique for this epitaxial layer by layer growth is called the molecular beam epitaxy and the most commonly used, not so precise technique is known as the chemical vapor depositions CVD technique.

So I already mentioned about the molecular beam epitaxy which is more accurate in terms of putting a few small layers of crystalline silicon of a certain direction on the top of a layer through a molecular beam which contains typically all the silicon atoms and other species. In the chemical vapor deposition however which can be done on large area substrates and which can be used for you know industry grade fabrication, high yield fabrication uses a set of chemical reactions.

For example there can be the use of silane or dichlorosilane as is illustrated here. Silane being $SiH4$ dichlorosilane being $SiH2Cl2$ where through high temperature and through cracking of this gas molecule you can generate silicon which is deposited as a solid phase or maybe silicon chloride $SiCl2$ and it can further liberate hydrogen in the process and then again the hydrogen which is excess in the particular chamber because of (()) (08:15) reasons again react to $SiCl2$ and formulate the silicon and acid residue.

So with the chlorosilane chemistry or with the normal silane chemistry using you know a cracking temperature of about 1200 degree Celsius one can generate solid films, thin films of silicon and that they are also crystalline in nature. So epitaxial layers can further be doped, doped by p-type or n-type material.

For example if the dopant gases like diborane phosphine are present in the same CVD system as the silane there is a possibility that it may deposit boron defects or phosphorous defects making it a p-type or n-type on the single crystalline silicon that has been grown by the CVD process. Already mentioned about the molecular beam epitaxy. The process is similar to an evaporation process using a silicon melt in a crucible where the entire beam which comes out is made of this beam.

So this silicon moieties and typically the MBE is limited process because of the fact that a high vacuum column would be needed to guide the beam which is being formulated and that severely limits the substrate sizes etc. So they are carried out under ultrahigh vacuum in temperatures ranging from 400 to 800 degree Celsius and the process is again the same, a few layers of silicon, pure silicon getting deposited from the beam on to the substrate which is otherwise a single crystalline silicon.

And so the substrate nature would be reflected in terms of the arrangement of silicon atom which happens because of deposition through the beam etc. So there are many other chemistries also associated with CVD, for example you could have silicon dioxide grown or nitrite grown or silicide grown based on what are the deposition chemistries that you are using. So this is also very well regarded as an additive manufacturing process where we are talking about depositing layer by layer of material okay.

So this falls under the category of the surface micromachining as had been illustrated towards the beginning when we talk about such MEMS fabrication.

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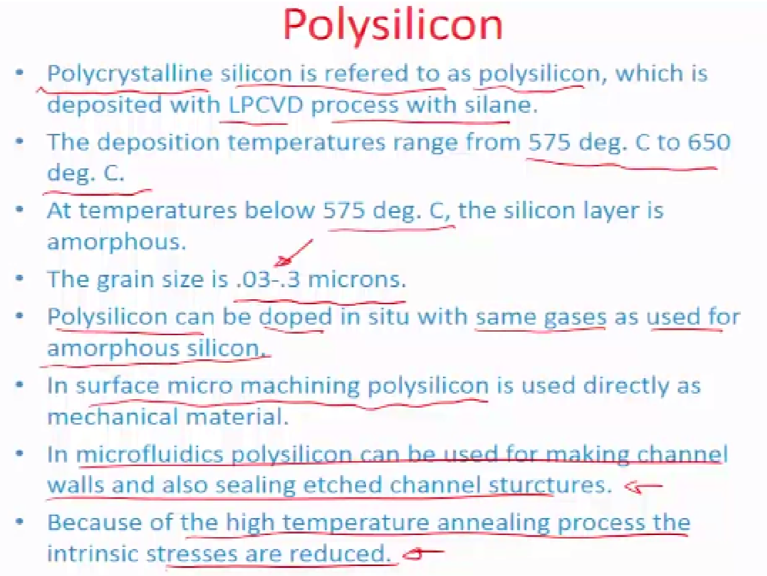

Polysilicon

- Polycrystalline silicon is refered to as polysilicon, which is deposited with LPCVD process with silane.
- The deposition temperatures range from 575 deg. C to 650 deg. C.
- At temperatures below 575 deg. C, the silicon layer is amorphous.
- The grain size is .03-.3 microns.
- Polysilicon can be doped in situ with same gases as used for amorphous silicon.
- In surface micro machining polysilicon is used directly as mechanical material.
- In microfluidics polysilicon can be used for making channel walls and also sealing etched channel sturctures.
- Because of the high temperature annealing process the intrinsic stresses are reduced.

The other form of silicon very commonly available is the polycrystalline form. The name suggests there are multiple crystal centers and each of them grow, nucleate, and formulate boundaries with respect to one another and therefore the polysilicon is considered to be mechanically tougher as a material. Polysilicon can be grown with low pressure chemical deposition process with either silane or a variety of other gases as you saw in the last slide.

Where the deposition temperatures for the polycrystalline silicon can range from 575 to 650 degree Celsius. A temperature below 500 degrees, 575 degree Celsius the silicon layer amorphous in nature. It converts its state from amorphous to crystalline beyond 575. The grain size which is typically obtained is about 30 to 300 nanometers and polysilicon can be doped also just as you dope the epitaxial silicon.

The doping can be carried out again with similar set of gases diborane or phosphine and polysilicon typically in surface micromachining is used for giving you know mechanically stable and robust materials you saw how a layer was deposited on a sacrificial material and the sacrificial material removed to create some kind of a small containment okay or confinement with the layer on the top.

So it can only be possible if the layer on the top is mechanically robust enough which can sustain the pressures created because of removing of the sacrificial layer from underneath. So in microfluidics the polysilicon can be used for making channel walls and also ceiling you know etched channel structures and because of the high temperature annealing process the intrinsic stresses are reduced and so one can estimate mechanically more robust material okay particularly ones which are crystalized at a higher annealing temperature.

So silicon now can be obtained in single crystalline form directly from the growth process or it can be grown using epitaxial methods where you have deposition of silicon atom by atom layer by layer and then you have the third form a polysilicon which is actually polycrystalline growth in multiple nucleating center with grain boundaries which is mechanically the most robust system of crystalline silicon that can exist. So that is how silicon can exist, coexist in its different forms.

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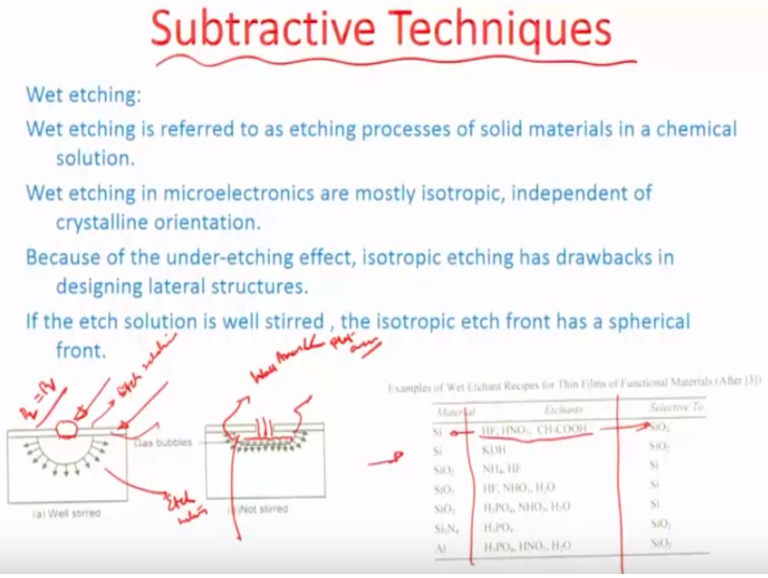

Subtractive Techniques

Wet etching:

Wet etching is referred to as etching processes of solid materials in a chemical solution.

Wet etching in microelectronics are mostly isotropic, independent of crystalline orientation.

Because of the under-etching effect, isotropic etching has drawbacks in designing lateral structures.

If the etch solution is well stirred , the isotropic etch front has a spherical front.

Examples of Wet Etchant Recipes for Thin Films of Functional Materials (After [3])

Material	Etchants	Selective To
Si	HF, HNO_3, CH_3COOH	SiO_2
Si	KOH	SiO_2
SiO_2	NH_4, HF	Si
SiO_2	HF, NHO_3, H_2O	Si
SiO_2	H_3PO_4, NHO_3, H_2O	Si
Si_3N_4	H_3PO_4	SiO_2
Al	H_3PO_4, HNO_3, H_2O	SiO_2

We will now go to once we have learned about silicon we go to some of the essential techniques for particularly MEMS application so we talk about subtractive manufacturing or subtractive techniques here. One of the most common techniques being wet etching. So wet chemical etching is basically the art of engraving into a solid material with some kind of chemical. The chemical could be an acid, it could be hydroxide chemistry and I am going to talk about this wet chemical process in great details.

You know typically you can categorize the wet etching techniques into either isotropic form or an isotropic forms or in the isotropic section we mostly discuss about homogenous you know material or material etch processes. Its rates are similar and not a function of the direction in which a thing is taking place. On the other hand in an isotropic chemistry, probably it depends on the direction which it takes and so typically what we do is in microelectronics shielding area and then create a small window or a vial through which you can then take the etching.

So in microelectronics one has to remember that there are 2 different broad classes of materials when we talk about etching processes. One is known as the etch selective layer. Another is known as the material that can be etched, okay so the etched material layer. So the etch material layer and etch selective layer has a in principle difference that the etch selective layer is where the etching will stop okay as the etchant meets that particular layer or that particular surface.

Whereas the etch material layer is one where whenever there is a you know interface of such a layer with a etchant it starts homogeneously etching out or anisotropically etching out. So this is the common difference between etch material and etch selective layer. So you should have for every chemistry that you are using a selective layer and a material layer and this is how it has been illustrated here.

So the different etchants which are used for example a combination of hydrochloric acid, HNO_3, and Ch_3COOH can be working on an etch material silicon but whenever there is SiO_2 this becomes very selective to it and stops the etching process and similarly in all these different materials you can have a common material and a selective material. So now the advantage is that whenever there is a selective material you can sort of use it to block the etching process okay from carrying forward anymore.

And that creates a very big advantage in terms of microstructuring because let us look at this particular example here where this material here is a sort of a you can say etch selective layer to the particular chemical that is being used. So what you do is you basically create a vial in this etch selective layer and you know put the chemical in close proximity so that the moment it touches the layer which is supposed to be the etch material.

In this case the layer underneath this particular layer is the etch material. So it starts etching away and if it is a homogenous process and if it is (()) (16:26) in all those actions you may expect that all the vertical and lateral etches are equal to each other. They are homogenous in all direction and you will have some kind of a hemisphere emerge because of this etching process. However, if you are not able to remove the material as quickly there is going to be some diffusion issues.

Because obviously the walls you know or the wall areas are much lower than the you know the flat area that means this particular area okay which is subjected to do etch. Let us call the flat area and because of which the flat area would have more etching and if you are not having a removal mechanism it is going to accumulate the etched particles or etched out particles and create a concentration around the flat because of which further movement of the etchant towards the flat maybe severely limited.

And because of which there may be a case of this under etching or lateral etching you can say which produces an under. So an undercut typically would happen because of lateral etching. So if materials are removed properly then undercut probably happens in a homogenous manner but if it is not removed properly then undercut happens in a very skewed manner and obviously whatever size or domain you are etching the overall etch profile that will eventually come out will be higher in size in width than the planned etching zone.

So therefore masks have to be designed in such cases and masks by masks I mean this particular etch selective layer it could be a resist, it could be some kind of a you know layer which is selective to a certain etchant but it has to be designed in the manner so that the vial which is there or the opening which is there is not exactly same as the size of the feature that you are intending to obtain but slightly smaller than that. So this is how subtractive techniques can be gripped into or wet etching can be gripped into.

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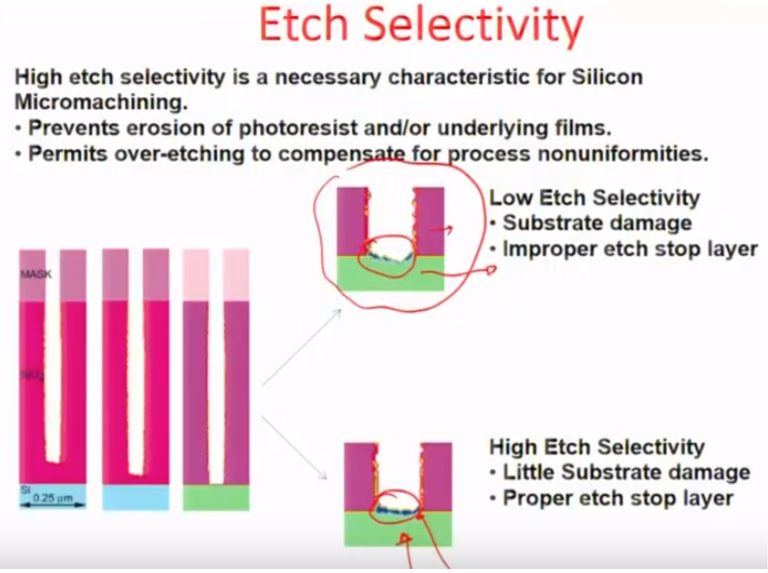

Etch Selectivity

High etch selectivity is a necessary characteristic for Silicon Micromachining.

- **Prevents erosion of photoresist and/or underlying films.**
- **Permits over-etching to compensate for process nonuniformities.**

Low Etch Selectivity
- **Substrate damage**
- **Improper etch stop layer**

High Etch Selectivity
- **Little Substrate damage**
- **Proper etch stop layer**

This is again another schematic showing the essence of selectivity so these are two different examples where you can see a poor selectivity given by the green material right here to a set of chemical which otherwise etch off the pink material okay but the same selectivity being more in this particular case would have a better impact in terms of the formulation of the interface. You can see the overall roughness of the interface formulated here and here are quite different. Here the interface roughness is lower because of the higher etch selectivity that the green layer has to offer. So this is how etch selectivity is kind of defined.

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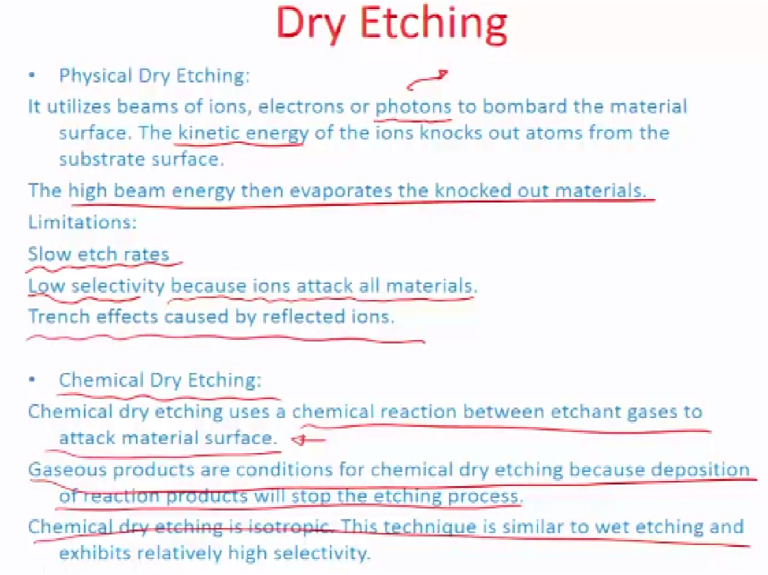

Dry Etching

- Physical Dry Etching:

It utilizes beams of ions, electrons or photons to bombard the material surface. The kinetic energy of the ions knocks out atoms from the substrate surface.

The high beam energy then evaporates the knocked out materials.

Limitations:

Slow etch rates

Low selectivity because ions attack all materials.

Trench effects caused by reflected ions.

- Chemical Dry Etching:

Chemical dry etching uses a chemical reaction between etchant gases to attack material surface.

Gaseous products are conditions for chemical dry etching because deposition of reaction products will stop the etching process.

Chemical dry etching is isotropic. This technique is similar to wet etching and exhibits relatively high selectivity.

Let us now look into another very important process which is about how etching can be carried out without wetting agents particularly you know etching can be carried out with the sort of physical particles knocking off material high energy beams for example or ions or laser and I am also going to talk about material where you know chemical gases are used for etching in a later on slide.

So essentially what happens in these physical dry etching processes is that there is a lot of kinetic energy which impact the particular surface because of which there is a there is a transfer of energy to the base material and a knocking off of the atoms on the surface of the base material which can be otherwise known as etching. Also due to certain you know energy mode being delivered into the material there is a chance of conversion of one kind of energy to the other.

For example in laser etching you use a bunch of photons which have high energy but the photons are converted into phononic vibrations of the surface bonds. Photons are absorbed within the material and because of the absorption there is a raise in the temperature or raise in the kinetic energy. So the mode converts from a photon to a photonic vibration. So that is how you can use different beams, high energy beams or photon beams to selectively remove or melt away or vaporize materials. So the high beam energy then evaporates and knocks out the materials.

Some of the limitations the process has to offer is that they are extremely slow on the etch rates because a sufficient amount of thermal excitation within the surface layers of a hard material is also very different process. The other issue is low selectivity in the wet etching case. You have a complete definition of a layer which is selective to the advancement of etching processes so the moment there is a layer like that which comes in the path of the etching it will automatically screen off the etching completely from going into the areas where they can affect.

But here in this case because of the ion attack and the rebounding of the ions etc. generally whatever is being attacked by the ion would have some kind of a thermal energy and melting or a vaporizing aspect. So there is not much selectivity unless there is a masking or shielding which is offered through a shadow mask which I will come to later probably when we do some you know talking about lithography processes.

So there are these rebounded ions which are or electrons maybe which are able to etch the surface but not probably to that level of roughness. There are certain trench effects caused by the reflected or bounced back ions from the surface and that kind of creates an overall higher roughness level. Also you have to remember because the material is melting and not getting carried away that fast.

There is going to be some kind of recyclement in terms of recrystallization and growth in those areas and so therefore the surface which formulates after the etching is not really very you know planar in nature and has to have some of the hybrid strategies coupled for making it planar like the secondary etching step for example incorporated in some of these processes. And by etching I mean chemical etching, with chemical etching.

So you have then chemical dry etching techniques where again there is a chemical reaction between the etchant gas in a manner that it attacks the material on the surface and carries away the material as in gaseous state. So for example silicon facing a you know chlorine gas or a fluorine gas would typically convert into SiF_4 or $SiCl_4$ and it can then be carried out because both of them are gaseous states and that way the silicon can go off the atoms or the solid surface.

So gaseous products are conditions for chemical dry etching because deposition of reaction products will stop the etching process; that is one. Also chemical dry etching is isotropic. The technique is similar to wet etching and exhibits relatively high selectivity.

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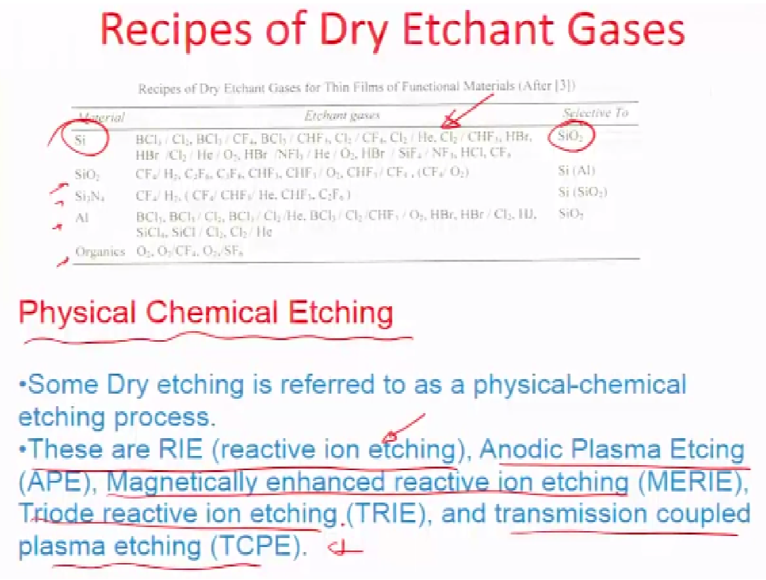

Recipes of Dry Etchant Gases

Recipes of Dry Etchant Gases for Thin Films of Functional Materials (After [3])

Material	Etchant gases	Selective To
Si	BCl_3 / Cl_2, BCl_3 / CF_4, BCl_3 / CHF_3, Cl_2 / CF_4, Cl_2 / He, Cl_2 / CHF_3, HBr, HBr /Cl_2 / He / O_2, HBr /NF_3 / He / O_2, HBr / SiF_4 / NF_3, HCl, CF_4	SiO_2
SiO_2	CF_4/ H_2, C_2F_6, C_3F_8, CHF_3, CHF_3 / O_2, CHF_3 / CF_4 , (CF_4/ O_2)	Si (Al)
Si_3N_4	CF_4/ H_2, (CF_4/ CHF_3/ He, CHF_3, C_2F_6)	Si (SiO_2)
Al	BCl_3, BCl_3 / Cl_2, BCl_3 / Cl_2 /He, BCl_3 / Cl_2 /CHF_3 / O_2, HBr, HBr / Cl_2, HI, $SiCl_4$, SiCl / Cl_2, Cl_2 / He	SiO_2
Organics	O_2, O_2/CF_4, O_2/SF_6	

Physical Chemical Etching

- Some Dry etching is referred to as a physical-chemical etching process.
- These are RIE (reactive ion etching), Anodic Plasma Etcing (APE), Magnetically enhanced reactive ion etching (MERIE), Triode reactive ion etching (TRIE), and transmission coupled plasma etching (TCPE).

You can see some of the gases or the gas recipes which are selective again to certain materials and are active to certain etch materials. So for silicon, silicon oxide, nitride, aluminum, and many organics you have different etch gases or etch chemistries between gases you know. So this is also similar to a CVD reactor where these gases are sent in at a controlled manner and they interact with the surface and create gaseous products of material coming off the surface and thus etch away or engrave the material in the process wherever they are exposed to or wherever the gasses can attack.

There is also another, yet another important you know etching aspect which is called the physicochemical etching where there is some physical means of attack by virtue of bias created within a system and then there is some chemical means of attack where there is a chemical reaction in place. These are known as RIE or reactive ion etching techniques. I will come into some details of this later as we have time for doing some processing for MEMS.

There is also anodic plasma etching. There is magnetically enhanced reactive ion etching, triode reactive ion etching and transmission coupled plasma etching. These are different process without getting into the details of these, these are some physicochemical. So you are using the power of the ionic state of gas that is plasma and then on one hand you are creating bias to impact so that the ions can impact a flat surface.

On another hand you are also creating small amount of chemical reactions with those ions which are impacting the surface then so that there can be some etching you know carried out in this manner. So I think I will like to close on this particular module. But in the next module I will look at another form of etching and some basic lithography and other processes which are important for you to understand before you proceed into how to design sensors and design actuators. So thank you very much for your attention. Thank you.