VLSI Technology
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Lecture - 27
Plasma Etching Systems

So, we are going to discuss about dry etching. As I told you that dry etching is in contrast with wet chemical etching, where we do not use a chemical solution, but we use plasma and I have told you also in the last class what plasma is, what are the basic features of plasma and inside the plasma what the potential at different points is.

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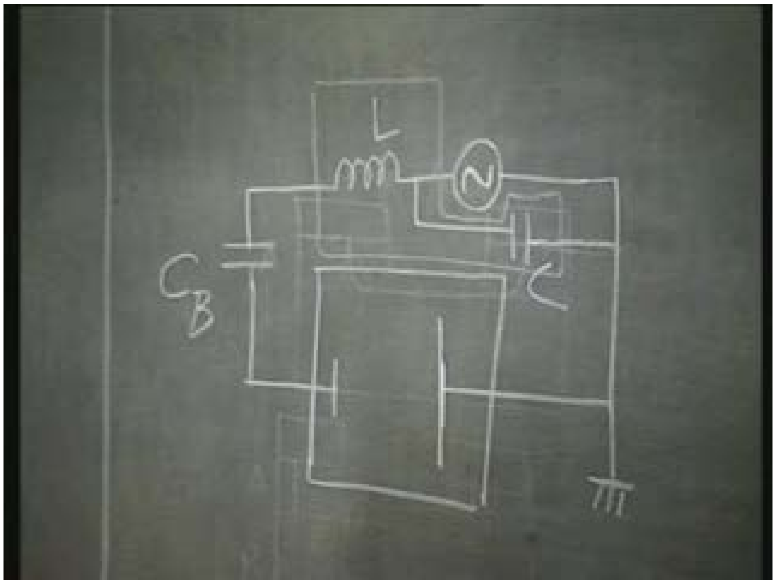

As you can already see here, usually in a plasma reactor we have a permanently grounded electrode, which we call the anode. So, therefore that anode is always at zero potential, right. If we have an insulating surface immersed in the plasma, then it is going to acquire a small negative potential which is called the floating potential and this is the floating potential.

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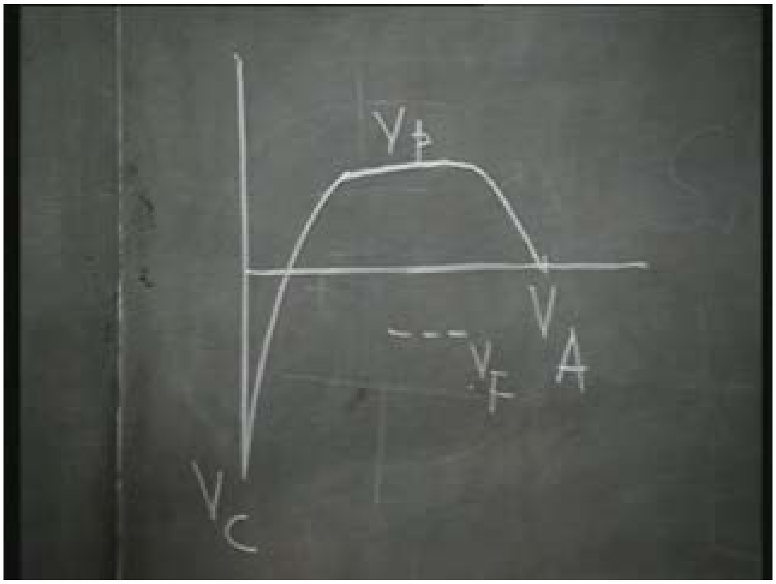

The center part of the plasma, it has a positive potential, because it is primarily comprised of positive ions, which are slow to move and that potential is called V p which is a small positive potential and the other electrode that is the RF powered electrode, it has a cathode sheath potential associated with that and that sheath potential can be considerably high. It is a high negative potential, the point at V C, right and we can further increase the cathode sheath potential if that electrode area is made smaller. When the electrode area is made smaller, the capacitance is going to be smaller, the impedance is going to be larger and therefore, the potential is going to be larger.

So, by reducing the electrode area, see, one electrode is smaller compared to the permanently grounded electrode, we can make the cathode sheath potential even higher. In addition to that, we can reduce the pressure inside the chamber and then, in order to sustain the plasma, the electrons must have higher energy and therefore higher potential or we can even reduce the frequency to a certain extent to increase the sheath potential and the potential difference between any two points will actually determine the electric field strength and consequently that will determine the ion bombardment energy. So, it is very important where you place your substrates. You know you have three possible places to put your substrate. One is the grounded electrode, one is the powered electrode and one is on an insulating surface inside the plasma. So, depending on where you place your substrate, the substrate is going to experience a certain electric field. I mean the ions are going to experience a certain electric field and therefore, they are going to bombard on the substrate with a certain energy, right.

So, with this background, let us now look at the etching mechanisms. But before that, let me remind you that in any etching system, we have two very important figures of merit. These are anisotropy and selectivity. So, you see, basically in plasma, you can have very high electron temperature, right. That is because the energy transfer between the electron and the plasma is very inefficient. So, electrons can acquire very high energy. Consequently their temperature, effective temperature can be very high, while the plasma temperature is still much smaller. What is the advantage? We can have high temperature like reactions. Let me expound on that slightly. What do I mean by high temperature like reactions? You know, in all the reactions we have some reactive species, right; some reactive species must be generated in order to take part in the reaction and most cases what happens, to generate that reactive species, we need to provide a certain amount of energy usually by means of raising the temperature; by providing thermal energy we generate the reactive species.

Inside plasma however, since the electrons have an effective temperature of 10,000 Kelvin, the reactive species can be generated without having to raise the total ensemble temperature; that is I need not have to raise the total temperature. Because the electrons are already at a very high temperature, we can facilitate the generation of this reactive species. So, inside plasma, therefore you can have a number of reactive species present, which will otherwise not be present. Without the plasma at that low temperature, 100 degree centigrade or so, those reactive species will not be generated if the plasma was not there. That is one aspect of plasma. The other aspect is of course by suitably adjusting the cathode sheath potential, it is possible to have very high ion bombardment energy. This is aspect number two. So, in plasma, we have basically two factors governing the etching mechanism. One is the ion bombardment energy and the other is the easy generation of reactive species.

Now, let us look at the etching mechanisms inside the plasma. I can have, it is possible to have chemical etching inside the plasma.

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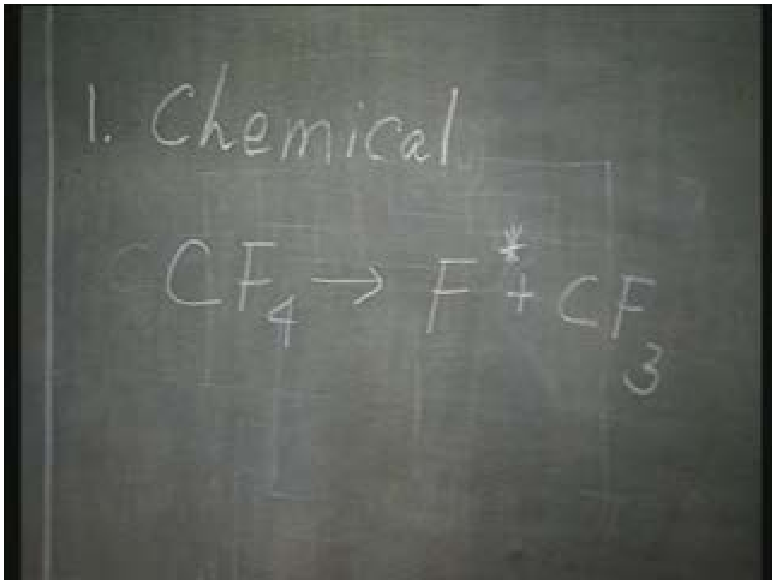

1. Chemical

$CF_4 \rightarrow F^* + CF_3$

Because of the high electron temperature, reactive species are easily generated and they can take part in the chemical reaction. The reaction product if it is volatile, then you will have etching. So, here the reaction is taking place in the gas phase, right; gas phase species, they are going to react with the surface, substrate surface and going to form a volatile product, which will be carried away from the reaction site and therefore, you have etching. Example is silicon etching in CF 4 plasma; CF 4, carbon tetra fluoride. In the plasma, you have active fluorine plus CF 3. Now, this active fluorine, it is not an ion; it is a neutral species, it is a neutral reactive species. So, the role of plasma here is limited to generating the reactive species; rest is spontaneous. This active fluorine species is going to spontaneously react with silicon, in order to generate a volatile product and therefore silicon surface is going to get etched.

That is if under, without plasma, in the normal circumstances, I could somehow generate this active fluorine species; that will also react spontaneously, I do not need plasma. I need the plasma only to generate this species. Normally, it is not possible unless you provide enormous amount of energy. Here that energy is being supplied by the hot electrons in plasma, these electrons which have acquired very high energy. So, the etching is chemical, no ions are involved in this. It is simply silicon reacting with fluorine. The role of plasma is, as I said, limited to generating the active fluorine species and because this reaction is chemical, it is going to be isotropic in nature.

All chemical etching is isotropic, right, because fluorine is not going to distinguish between the side wall silicon or the horizontal plane silicon. Wherever it finds silicon, it is going to react with that. Therefore you will have under-cuts; your etching is going to be isotropic. But at the same time, because it is chemical, its selectivity is going to be very good. It will react only with silicon, even not with silicon dioxide. You know, using CF 4, you can in fact get a selectivity ratio of 40 is to 1 between silicon and silicon dioxide. So, this is one end of the spectrum of etching mechanisms possible with plasma; one end of the spectrum that is chemical etching.

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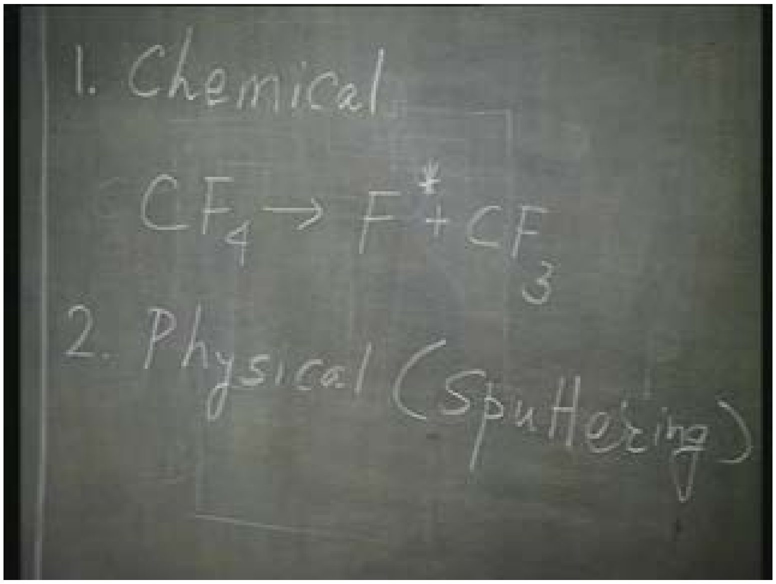

1. Chemical

$CF_4 \rightarrow F^* + CF_3$

2. Physical (Sputtering)

Let us go to the other end of the spectrum and as opposed to chemical etching, I should call it physical etching, right or it is sometimes referred to as sputtering or ion milling. This is where I am taking advantage of the high ion bombardment energy. If the ions have a very high energy, because of the very large sheath potential, so they impinge on the substrate surface with a very high energy. That high energy is sufficient to dislodge the surface atoms. So, the surface atoms get ejected out. So, this is simple physical removal. By brute force, you have very energy particles coming and hitting the surface and in the process, ejecting out surface atoms and the etching takes place. You understand? So here, the selectivity is going to be the causality, because whatever surface, whatever substrate you have put in, high energy particles, high energy ions are going to be impinging on that surface and physically remove material. So, it is not going to distinguish that well between silicon and silicon dioxide or whatever.

But, it is possible to realize very good anisotropy. Because, you see, suppose this is my substrate surface; ions are getting impinged like this. So, only on the surface on which it is getting impinged, see, you can see the surface particles getting dislodged, right; only on that surface etching is taking place. What about the sides? It is not falling on the sides; just falling on this surface, but not here. So, the side walls are protected, right. I can realize good anisotropy. I can etch only one surface preferentially, right; whichever surface is exposed, whichever surface is normal to the incident of the ions, only that surface is going to get etched, but selectivity is going to be causality. So, these are the two ends of the spectrum - chemical etching and physical sputtering. In one, I have good selectivity, but poor anisotropy. In the other, I have poor selectivity, but good anisotropy.

Now of course, we can think of a possible combination of these two, how these two phenomena can be combined and I can get the best of both worlds that is I can get good anisotropy as well as good selectivity.

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3. Energetic
Ion-enhanced

So, we come to the third method of etching and that is called energetic ion-enhanced etching. Even though I said that we can try to combine, do not take it too literally, because it is not really a combination of the first two processes. It is a different process altogether, but where we have managed to optimize the characteristics of these two types of etching. In energetic ion-enhanced etching, what happens is that ions are impinging on the substrate surface, but their energy is usually much less than in case of this physical sputtering, so that this ion energy is not really sufficient to cause physical etching. What it does instead is it makes that surface more reactive. It makes that surface more reactive, so that now it can react spontaneously with the chemically generated species inside the plasma and etching can take place.

I will give you an example. Suppose I want to etch silicon with chlorine. Now, if you have moderately doped silicon, not very heavy doping, moderately doped silicon or intrinsic silicon, undoped silicon, then chlorine does not react spontaneously with silicon, not even in plasma. But if you have plasma and if you have sufficiently high ion energy, then these ions can make the silicon surface more reactive, so that the reactive silicon surface can react with chlorine and get etched. Do not think it is a combination of two; it is not a combination of the two. This is verified by, if you put instead of chlorine, a neutral I mean inert gas, for example, suppose instead of chlorine you put Argon. Now, my contention is if the etching is done simply by physical sputtering, then it does not matter what ion is impinging on silicon surface, because no chemical reaction is taking place. All that matters is that ions with sufficiently high energy should impinge on the surface and eject surface atoms. So, if instead of chlorine I put Argon, the result should be the same, if it was physical sputtering.

Experimentally it is verified that it is not the same. Instead of chlorine if you put Argon, then it is found that the energy of the ions in that range is much smaller. It does not really cause much physical removal of particles. But if instead of that you put chlorine, then chlorine does not, chlorine ions do not straight away bombard and eject silicon atoms, but it makes the surface more reactive. The ion bombardment is causing the reactivity of the surface to get enhanced, hence the name energetic ion-enhanced. The reaction is enhanced; the surface reactivity is enhanced by energetic ion bombardment. But, usually the energy of these ions is much smaller than what you need to cause physical sputtering.

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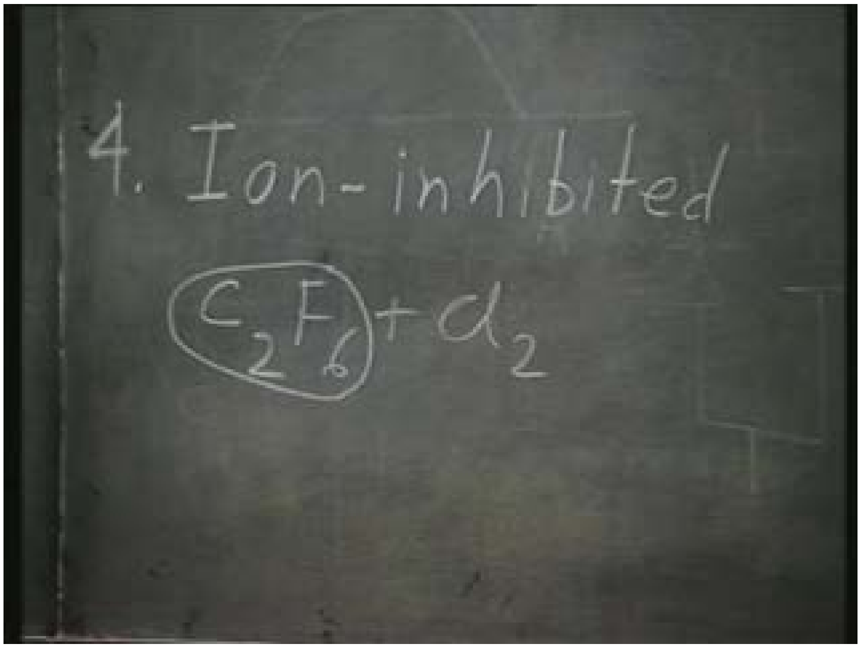

4. Ion-inhibited

$C_2F_6 + Cl_2$

So, it is not really a combination of one and two; it is a different phenomenon and I have a fourth mechanism, which is called ion-inhibited. Again let me take up an example. Ion-inhibited etching; let us say I am trying to etch heavily doped silicon with chlorine. Now, heavily doped silicon will react with chlorine spontaneously. Unlike intrinsic silicon where the spontaneous reaction does not take place, heavily doped silicon will react with chlorine spontaneously. So, this will be a chemical etching and therefore you will have isotropic etch profile, anisotropy will be poor; because it is a chemical etching anisotropy is going to be poor, right.

Note if you add an inhibitor along with chlorine, usually the inhibitor that is added is C 2 F 6. This C 2 F 6 is the inhibitor. The role of chlorine is still just the same. Chlorine reacts spontaneously with silicon, but what is C 2 F6 doing? C 2 F 6 is forming an inhibitor film on the surface. It is forming a protective film, so that the surface cannot react with chlorine. Now, think about it very carefully. I am saying that C 2 F 6 is forming a protective film, an inhibitor film on the surface, so that the surface cannot react with chlorine. The logical question is in that case how will etching progress? Etching itself will stop if the surface is protected, right.

The entire etching does not stop, because of the energetic ion bombardment. You still have ion bombardment in the plasma. So, on the surface on which ions are getting bombarded, the protective film is getting removed. So, the surface normal to the incidence of ions, this surface, that surface on that the inhibitor film cannot form; as soon as it forms, it gets removed. So, that surface is free to react spontaneously with chlorine. What about the side walls? On the side walls, the inhibitor film stays; it cannot get removed, because on that surface I do not have any ion bombardment. So, only the side walls effectively are protected by the inhibitor film. Only the side walls cannot react with chlorine. Result is good anisotropy as well as good selectivity.

So, here you see four basic mechanisms of etching. The first two, we have already discussed. One is chemical, analogous to wet chemical etching; the only difference is instead of having it in a solution media, you have the reaction in gas phase; that is the only difference. But, it is just a chemical reaction, therefore the etch profile is going to be isotropic. Selectivity, of course is going to be good; selectivity is the hall mark of any chemical reaction.

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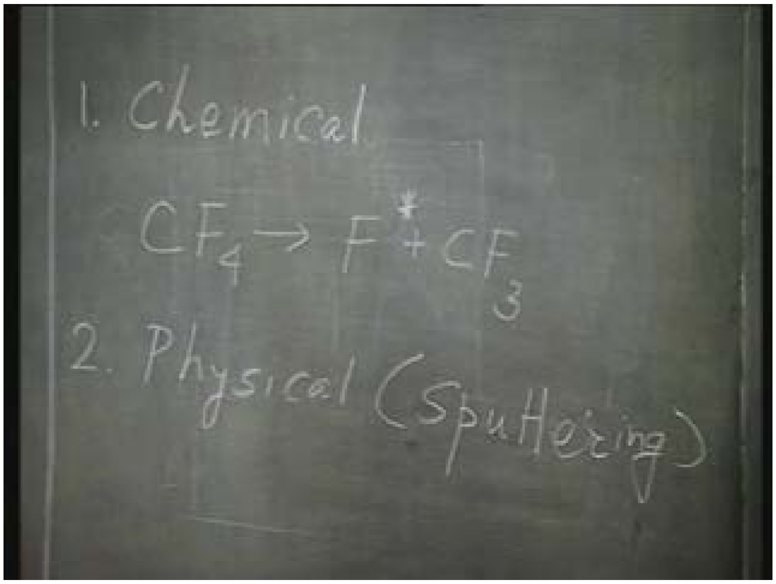

1. Chemical

$CF_4 \rightarrow F^* + CF_3$

2. Physical (Sputtering)

In the second process, we have physical removal of material, therefore selectivity is the causality; it does not distinguish between many substrates, it just removes the surface atoms by brute force.

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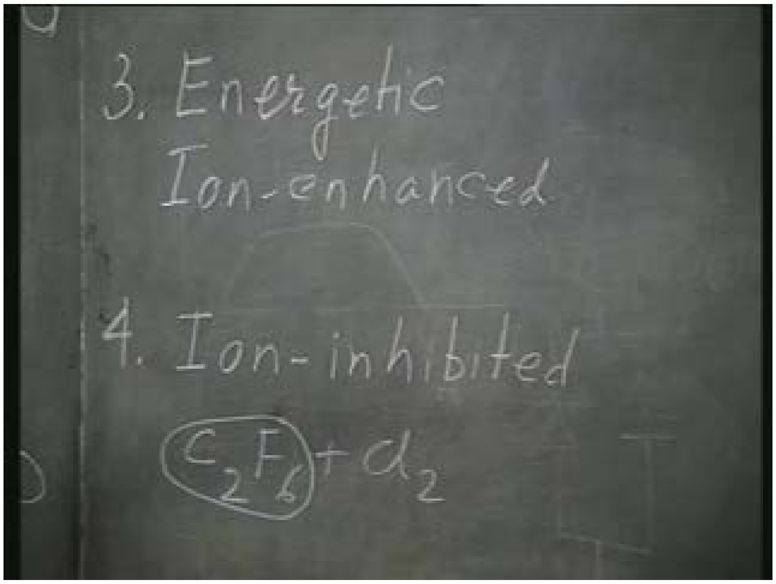

3. Energetic Ion-enhanced

4. Ion-inhibited

$\boxed{C_2F_6} + Cl_2$

In the third technique, we have energetic ion-enhanced, in which case the bombardment of energetic ions is going to increase the reactivity of the surface. So only that surface on which I have ion bombardment is going to have enhanced reactivity, only that surface is going to get etched consequently. So, in this process three, I can have good selectivity as well as good anisotropy. Good selectivity, because finally the reaction is chemical reaction; good anisotropy, because the reactivity of only a particular surface is getting changed, not of all other surface and then in fourth I have ion-inhibited, which in a sense you could say is the mirror image of process number three. Here, instead of enhancing the reactivity on certain surface, I protect certain surfaces by forming an inhibitor film over them.

The inhibitor film cannot form on the surface which is exposed to ion bombardment, because the ion energy will be sufficient to remove the inhibitor film. So, these are the four basic etching mechanisms and by judiciously applying them, you can have any kind of etch profile you want to obtain. So, again just as in case of diffusion and ion-implantation, implantation gave you much better flexibility, similarly dry etching is going to offer you much better flexibility in terms of etching profile compared to wet chemical etching.

So, now let us talk about the different reactor devices. Now that we know about the etching mechanisms, it is going to be very simple to talk about the reactor designs and you can yourself see which reactor should be used for what purpose. So, the reactors are actually, in fact in this context I should tell you that there are a lot of misnomers; you know, terms which do not really convey the right meaning. For example, we keep on saying reactive ion etching or plasma etching, without really stopping to think what they mean. Reactive ion etching - does it really mean that ions are taking part in the reaction, ions are reactive? Not really; hardly ever ions take part in reaction, very rarely.

Similarly, plasma etching; well, all of them can be said plasma etching or plasma assisted etching, because we are employing the plasma in some means or the other. So, these terms do not really convey exactly what is happening inside the reactor. So, it is better to define the reactors according to their geometry and from the geometry, you see you can very easily figure out what is the type of etching mechanism that is being employed here and whether we can realize anisotropic and or selective etching using these reactors.

The oldest reactor, oldest plasma reactor to be used for etching which is now quite obsolete is a barrel reactor.

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i) Barrel Reactor

0.1 – 2.0 Torr

So, this is only historical significance. A barrel reactor is exactly what it says. It is a barrel; it is a quartz barrel. You have a quartz chamber usually a spherical kind of a chamber like a bulb and the wafers are held in an insulating surface, in a floating surface inside this chamber. The pressure is on the higher side, 0.1 to 2 torr and usually it is inductively coupled. That is you have a coil wound round this barrel to couple it to the RF source. So, I have given all the clues. Wafers are held in an insulating surface inside the plasma. Therefore the potential, the sheath potential is going to be the difference between the floating potential and the ground. It is going to be a small potential, small negative potential. Consequently the substrate is going to experience a very small ion bombardment energy, right.

Since the sheath potential is very small, it is going to experience a very small ion bombardment energy. Pressure is also comparatively high 0.1 to 2 torr. It is on the higher side. So, ion bombardment energy is going to be quite minimal. Therefore the etching is going to be purely by chemical means. So, the etch profile is going to be isotropic. As I said, this barrel reactor is nowadays quite obsolete and it is only used to remove photoresist, if at all it is used. You have oxygen plasma and if you have a photoresist coated wafer, you know photoresist is an organic compound, it will react with oxygen and it will get ashed. So, it is used only for that, ashing of photoresist, removal of photoresist where you are not really bothered about the etch profile or anything. It is a very primitive form of a dry etching system.

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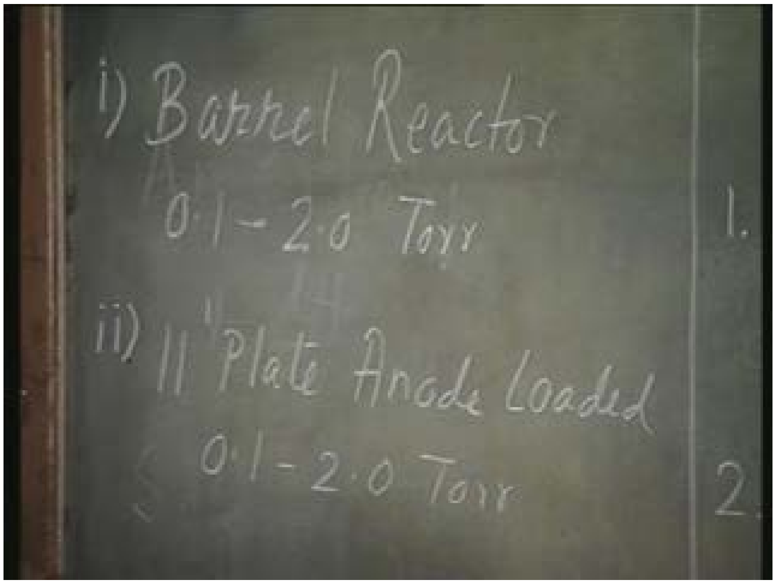

i) Barrel Reactor

0·1 - 2·0 Torr 1.

ii) || Plate Anode Loaded

0·1 - 2·0 Torr 2.

Then, we have what is commonly referred to as a plasma reactor. We will not call it plasma reactor, because all of them are plasma etching system. We will call it a parallel plate anode loaded reactor. Here also the pressure is the same as in case of a barrel reactor, right. So, that tells you all; it is a parallel plate anode loaded. Both the electrodes have the same area; wafers are loaded on the anode that is the permanently grounded electrode and the pressure is on the higher side, 0.1 to 2 torr. Usually one uses a RF frequency of 13.56 mega Hertz. That is the most common RF frequency to be used in all the plasma reactors.

So, again you see, the anode sheath potential is actually going to be quite small. It is just the difference between the plasma glow potential, V p and the ground potential. That is actually the electric, the potential difference the ions are going to experience, isn’t it. So, even here we can say that the ion bombardment energy is going to be very small and therefore, the etching is going to be by chemical means only. So, you have good selectivity, but relatively poor anisotropy, unless of course you use special additives as inhibitors, right. Normally the reaction is going to be chemical and therefore, the etching profile is going to be isotropic. Anisotropy will be poor unless you add inhibitor forming gases like C 2 F 6, so as to improve its anisotropy, right.

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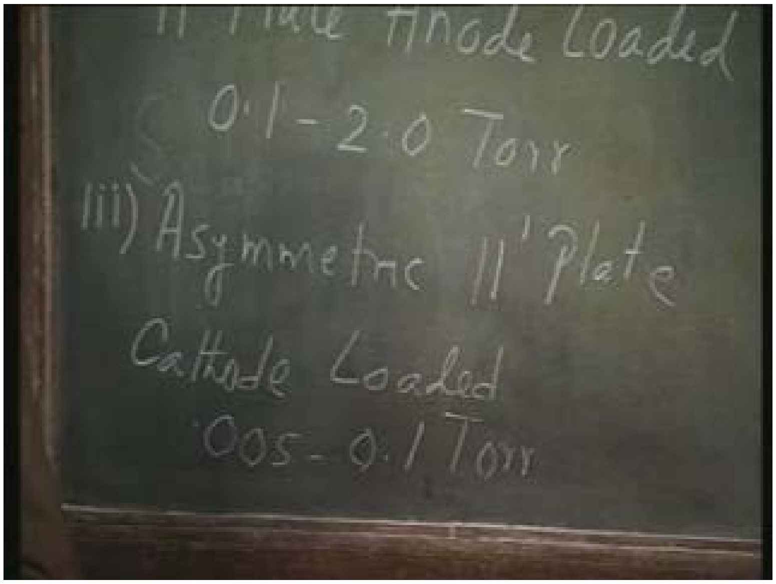

|| Plate Anode Loaded

0·1 - 2·0 Torr

iii) Asymmetric ||' Plate

Cathode Loaded

·005 - 0·1 Torr

The next one in the line is usually called the reactive ion etching system, but as I told you that again do not convey the actual meaning, because ions hardly ever actually take part in the reaction. So, instead of that, we will call it asymmetric parallel plate cathode loaded reactor. Here the pressure also is going to be much smaller, 0.005 to 0.1 torr. So again, you can figure it out for yourself. It is asymmetric parallel plate, so one electrode is smaller than the other. Which electrode should be smaller, obviously the cathode, right; because I want to increase the cathode sheath potential. I am further increasing the cathode sheath potential by reducing the pressure, right. Therefore the substrates which are placed on the cathode that is what the significance of cathode loaded means, right, that the wafers are now loaded on the cathode, so they are going to experience very high ion bombardment energy, quite high ion bombardment energy. Therefore, I can have reaction type 3 or 2 or 4, whatever I want, right.

So, if you notice from 1, 2, 3, I am slowly increasing the ion bombardment energy. The barrel reactor as I said is quite obsolete, nobody uses barrel reactor any more. So, let take 2 and 3. In 2, I had same parallel plate electrode configuration, but the two electrodes were of same area, so that cathode sheath potential was not very high and wafers are loaded on the grounded anode, so anyway they experience a smaller ion bombardment energy, pressure was also low. Now, in the asymmetric parallel plate cathode loaded type, we are loading the wafers on the cathode which is smaller in size, therefore cathode sheath potential is much higher and also the pressure is low, so that the ion bombardment energy is even more and therefore we can have energetic ion-enhanced reaction or ion-inhibited, yes of course, why not, or even some amount of physical etching is possible.

In the same line we can continue and we can go to an etching system, where we totally do away with the chemical etching. See in all these cases, I have one element of chemical etching, right. But, if I have very high ion bombardment energy, then I can totally do away with chemical etching and I can have only physical sputtering. So, that reactor, it is called the inert ion-beam etching.

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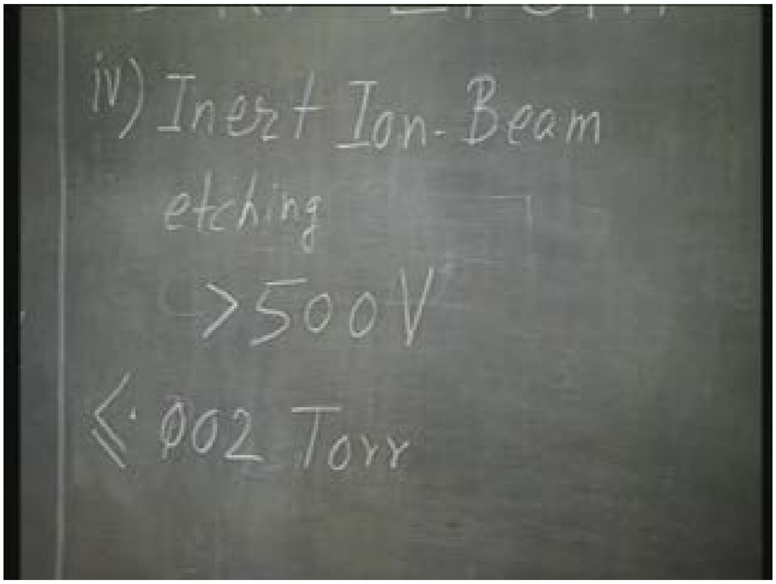
iv) Inert Ion-Beam
etching
>500V
<.002 Torr

There is a difference of class, totally. In the first three cases, we had chemical reaction as the dominating means of etching. It could be energetic ion-enhanced reaction or ion-inhibited reaction or pure and simple chemical reaction, but the chemical reaction was always a very important role to play in the first three types of etching, first three types of reactor. Now, we have come to a system which is inert ion-beam etching, where we do not have any chemical reaction at all. So, what we have? We have an inert gas like argon or neon, something like that and usually these are two zone systems. In contrast, all these are single zone systems. The first three cases, all these are three zone systems that is plasma is created in the same place where the wafer is kept. They are all in the same zone. In between the two electrodes plasma is created and on one of the electrodes the wafer is loaded, right.

In contrast, in ion beam, inert ion-beam etching we have two zone system, where the ions are generated in one zone that is generated by electron bombardment of an inert gas, usually argon is used and then they are accelerated. They are accelerated through one or more sets of grid to the second zone where the wafer is kept. So, you have a high energy accelerated, directed ion beam. Ions are created in one chamber. Now, they are passed through a grid, they are accelerated. It is a focused ion beam which is going and hitting the wafers kept in a separate zone, right. Obviously, here since I am relying completely on physical removal of particles, the ion energies must be very high, whereas in this case I had sheath potential of tens of volts; in this case may be, 100 volt, maximum sheath potential, in this case less than 20 volts.

Here, we have greater than 500 volts. The ion energy is equivalent to greater than 500 volts and the pressure is also much lower. In that case I had the lowest spectrum, lowest end was 0.005. Here it starts with 0.002, right. Actually the pressure is less than or equal to 0.002 torr. So, you need to have very low pressure, very high energy ion beam, in order to cause real physical removal. So, anisotropy is going to be very good. Because you have a focused directed ion beam, only those surfaces which are exposed to this onslaught of ion beam, it is going to get etched; side walls are going to be completely protected. But, this high energy ion beam is not going to distinguish between the different types of surfaces, so selectivity is the causality, right. You have very good anisotropy, but you have very poor selectivity.

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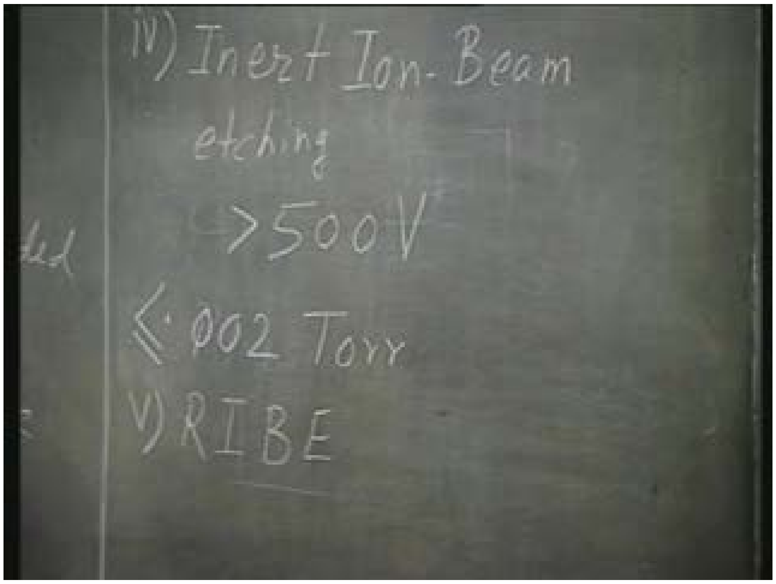

iv) Inert Ion-Beam etching

>500V

<.002 Torr

v) RIBE

To improve the selectivity to a certain extent, there is a variation of this which is reactive ion-beam etching. This is inert ion-beam etching; in contrast this is reactive ion-beam etching, RIBE. Now, only difference is instead of using an inert gas, you use a reactive gas, so that there is some amount of chemical reaction involved and you can distinguish between different surfaces, so that some kind of selectivity is obtained there and then finally, we have what is called microwave plasma. All these cases, all these reactors, I said that they generally operate at RF, 13.56 mega Hertz. That was the most common RF frequency employed in all these plasma reactors.

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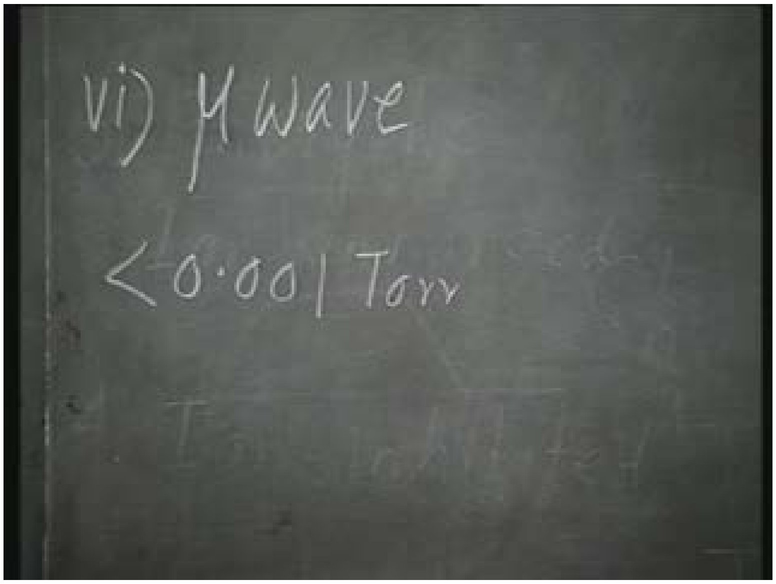

vi) μwave

< 0.001 Torr

In contrast, we have microwave plasma; usual frequency is 2.45 giga Hertz. So, you can have very dense plasma at microwave frequency and this will have very low sheath potential. You may ask me why I need this very low sheath potential. This is when you are particularly bothered about damages. Suppose for various devices, I need to etch, I need to etch in the active region. Whenever you are having bombardment with high energy ions, it is going to create some damage and in some cases this damage can be unacceptable. So, in that case you may want to use still a dry etching, but where the damage will be much less and in such specialized applications, one can use microwave plasma, where the sheath potential is very low and consequently damage is very, very low.

So, usually, of course because the sheath potential is very low, you will have isotropic etching, but if you go to very low pressure, less than 0.001 Torr, then you can get some anisotropy and another variation of this microwave plasma reactor is called a downstream reactor, where you have two zones. Plasma is confined in a remote chamber and the wafers are held in another chamber. So, then again you have some directionality, anisotropy can be improved; some directionality is there, so anisotropy can be improved. So, microwave plasma is for specialized applications, microwave plasma etching. Where you are very particular about the damages, you are going to etch in the active region; you are very particular about the damages and therefore you want to keep the sheath potential minimal, but at the same time you would like to have a dry etching technique.

So, you see, it makes sense to distinguish, to talk about the different reactors according to their geometry, because the geometry correctly tells me what is the etching mechanism possible in this particular reactor? That is why I prefer not to use the commonly used term such as plasma etching or reactive ion etching and go for the geometry based approach. That is you call it parallel plate anode loaded or asymmetric parallel plate cathode loaded or you call it inert ion-beam etching or whatever, which tells you without any ambiguity what the etching mechanism is. So, so far, we have just generally talked about the dry etching system, right. What is happening inside; what is happening, what are the etching mechanisms possible, what can you do to enhance one factor over another? What can you do to enhance the chemical reactivity, what can you do to form the inhibitor film, etc, etc.

Now, we are going to talk about the special etching systems. That is suppose I want to etch silicon. That is my prime concern; I want to etch silicon or silicon dioxide or silicon nitride. How do I do that? Now, the etching of silicon can be done, is done usually, by following one of the two paths. You can either have a fluorine based etching or a chlorine based etching, depending on what your requirements are.

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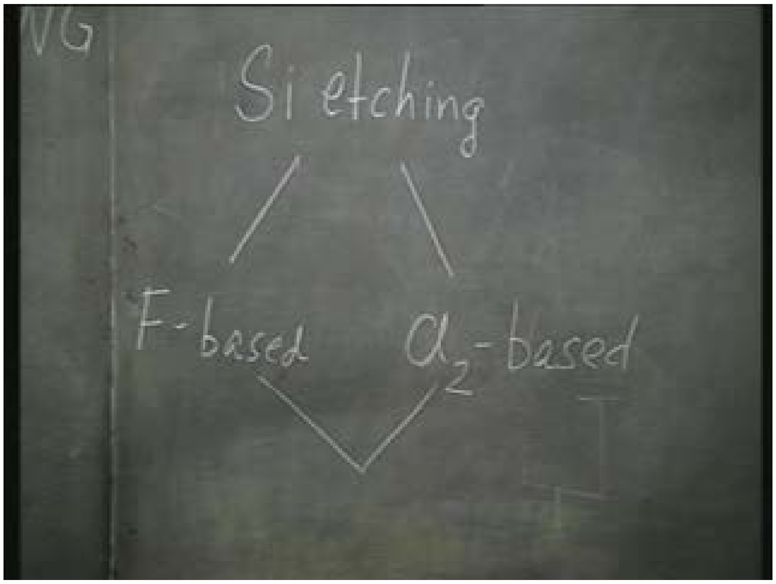

It can be fluorine based or it can be chlorine based. In case of fluorine based reaction, the reaction is going to be spontaneous. So, you will have isotropic profile, but with very good selectivity. On the other hand, if you have chlorine based reaction, then the reaction will depend on various factors; for example on doping of silicon. If it is moderately doped or not doped, then chlorine does not spontaneously react. Therefore, you should have sufficiently high ion energy, so that the surface can be made reactive, right; energetic ion-enhanced. On the other hand, if you have heavy doping in silicon, then chlorine is going to react spontaneously. Therefore, if you want to have anisotropy, you must have an inhibitor forming mechanism, like you should have C 2 F 6 with chlorine; that will give you better anisotropy.

In contrast, the reaction with fluorine is spontaneous and vigorous and even adding inhibitor is not going to help, because the reaction is so vigorous. So, in fluorine you are constrained that the etch profile is going to be isotropic, whereas in case of chlorine, you can play; you can have an anisotropic profile. So, it is also possible to have a route, which is a merger of the two. I can have in the feed gas, a combination of chlorine and fluorine to tailor the etch profiles. By varying the feed gas composition, I can go from completely isotropic to completely anisotropic profile. So, this is what we are going to explore in the next class.