VLSI Technology

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Lecture - 26
Dry Etching

In the last class, we have talked about chemical or wet chemical etching. That is when you put the material that is to be etched in a chemical solution and some reaction takes place and the material gets etched. We have however encountered a problem there particularly when the device dimensions become smaller. That is when the region to be etched is a very small area.

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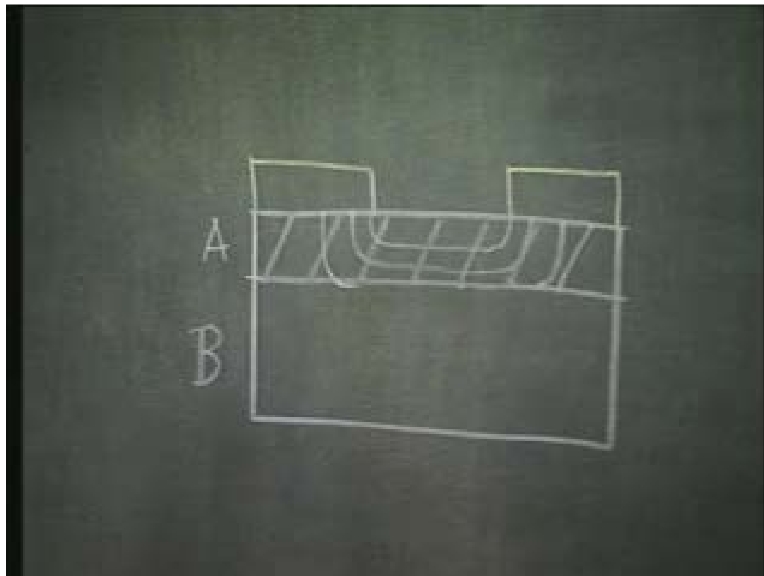

For example, we have chosen a particular example. The shaded region is a material, let us call it A and the rest of the portion is another material called B. It can be silicon dioxide on silicon, it can be silicon nitride on silicon, it can be aluminum on silicon; it can be anything. Anyway, the point is that I have certain area on the top surface masked and I want to etch only through this opening. When the etching is chemical, then the etchant material cannot distinguish between the vertical and the horizontal surface. That is to say etching will progress both on the vertical surface as well as on the horizontal surface and

therefore the etching will progress actually like this, like this and like this, so that finally I shall have an etch profile with a lot of under-cut.

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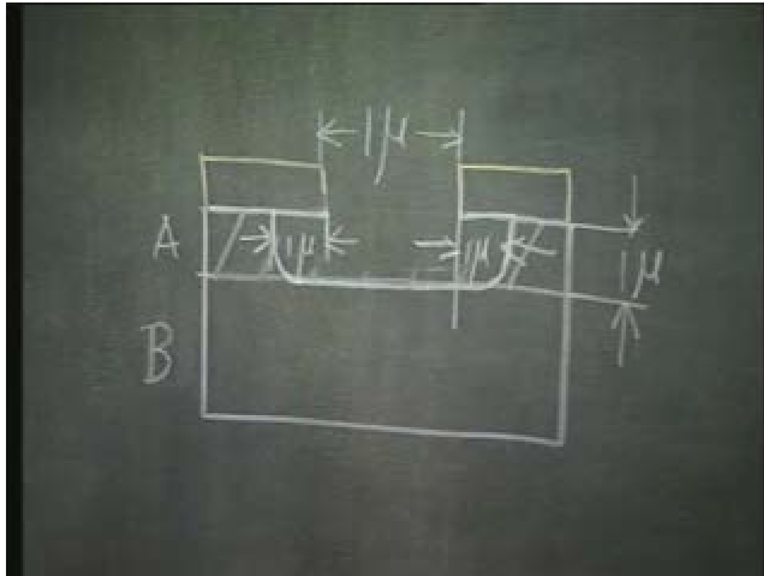

It will look like this and if this dimension that is the dimension of the window, the window opening is let us say, 1 micron and if the thickness of this is also 1 micron and if I say that the etching solution cannot at all distinguish between the horizontal and vertical surface that is it is perfectly isotropic, perfectly isotropic that means it cannot distinguish on horizontal or vertical surface. It etches exactly in the same rate both the horizontal as well as the vertical surfaces. In that case, you will find that whatever depth it has gone in the vertical direction, it will be the same in the horizontal direction also. So, even this dimension is going to be 1 micron and this is also going to be 1 micron. So, even if I started with 1 micron window size, at the end of the etching I have actually realized a feature which is 3 micron wide.

This is of course absolutely not tolerated, particularly when the device dimensions are becoming smaller. It cannot be tolerated, because if I have to tolerate that that means in between two such features I need to have a lot of space. But, the problem is not just this much. Suppose your requirement is such that you want the entire material A to be

removed; through this window you want to make sure that the material A is completely removed. One way to ensure that will be to put it in an etchant solution which does not at all etch B and leave it there for a considerable amount of time. You want to ensure that all trace of material A from the top surface has got removed, right. This is the common practice when we want to do a little bit of over etching. We call it over etching. That is I know that this particular etching solution is not going to etch B that is the etch rate of B is going to be very, very small, so I do not bother about that; I just want to make sure that the material A does not remain.

For example, let us say before an epitaxy you want to make sure that all traces of native oxide is removed, you want to ensure that. So, you put it in hydrofluoric acid for some time, more than necessary. That is the concept, right. Now here, the problem is very funny. I have put it in this etchant solution. The material A is getting etched and finally I come to the interface of A and B that is at this line. Remember, I have no way of precisely determining what the time instant is, right. Therefore, to be on the safe side, I am going to leave it in the etchant solution for a longer period. So, what happens? From the instant I have reached the interface between A and B to the etchant solution, the etchable surface is only the side walls. It does not etch B, so the etching virtually stops here. But, it can keep on etching the side walls. So, what will happen?

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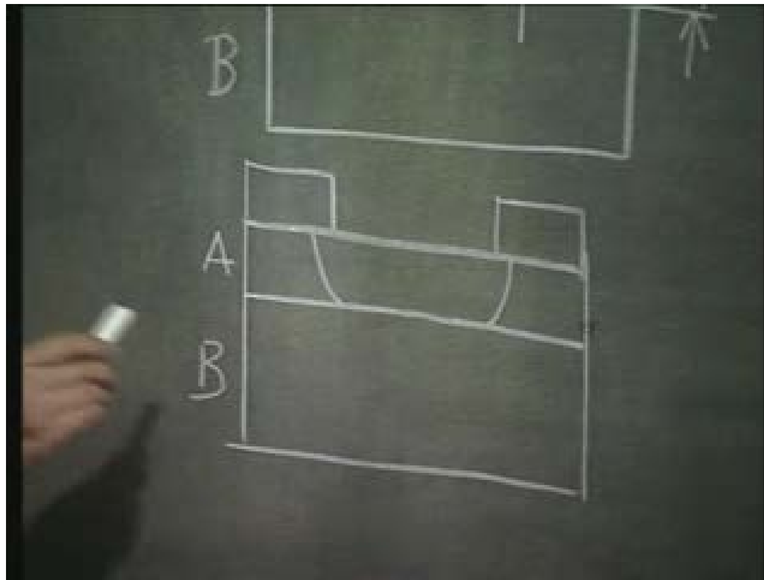

If I keep it for a longer duration than that is necessary what I will have is something like this. Let us say, this is my material A, this is my material B and what I will have will be like this and then, since I have only the side wall surfaces, etching will progress very fast on the side wall, because now all the etchant solution is doing is etching the side walls.

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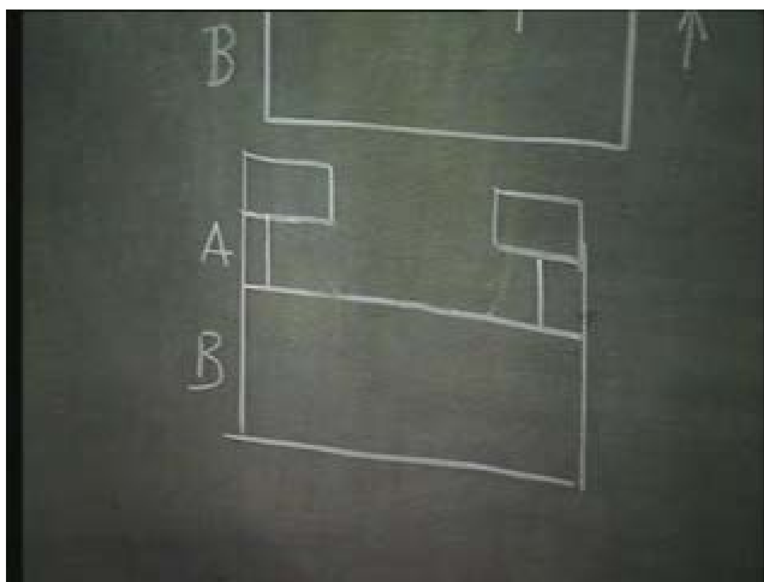

So, I will have almost vertical side walls. Do you realize the problem? The problem is two-fold. First of all, anyway I am going to have an under-cut, because the etching solution is etching both the horizontal and the vertical surfaces if not exactly at, precisely at the same rate, at least at comparable rate. So, I anyway have under-cut.

Now, to make matters worse, when I want to ensure that the material A has got completely etched from my window, I leave it for a duration longer than that is strictly necessary. Now, the etchant solution can keep on etching the side walls and therefore, I have a much larger under-cut, when what I wanted is precisely a reverse. I wanted to control the etching when the etching is near its end point. Instead of that, now I have a very severe under-cut problem, if I want to ensure that the entire material A has got etched. This is a very common and very severe problem associated with all wet chemical etching and as the device dimensions are becoming smaller, for fine geometry etching therefore, we use a different technique which is different from wet chemical etching and it is called dry etching, as opposed to wet etching; dry etching that is the etching is no longer done in a chemical solution.

Remember in deciding the merits of any etching system, there are two factors. One is the anisotropy of etching and the other is the selectivity of etching. So, these are the two figures of merit for any etching system.

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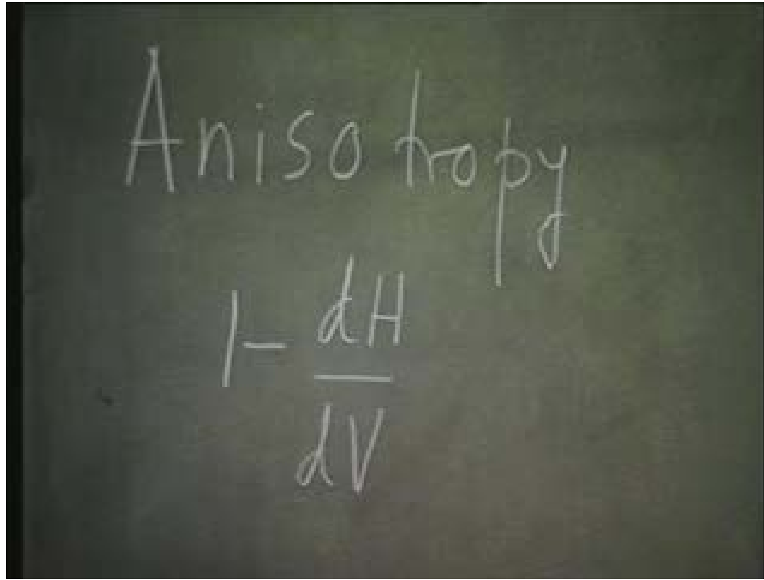

Anisotropy - what does anisotropy mean? That is I must ensure that etching takes place preferentially in one direction. For example, in this case I would have liked to ensure that the etching takes place only in this direction and not in this direction, so that I have minimal under-cut. I want only etching in the vertical direction. So, anisotropy is usually given as a ratio between the horizontal etch rate to the vertical etch rate. So, you can say anisotropy is 1 minus dH dV; dH is the etch rate in the horizontal direction, dV is the etched rate in the vertical direction. So, let us say if an etching system is such that the etching rate in the horizontal direction is zero, then it is perfectly anisotropic. Anisotropy is 1, dH is zero, therefore it is perfectly anisotropic. On the other hand, I would say that an etching system is perfectly isotropic when it etches precisely at the same rate. In other words, dH dV is 1, so that anisotropy of the system is zero. That means the etching is perfectly isotropic. You get it?

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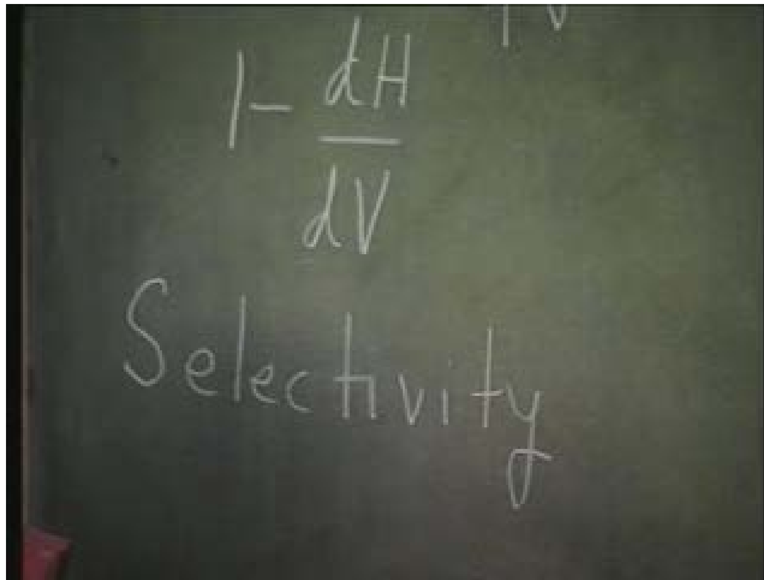

The other figure of merit for any etching system is its selectivity and what is selectivity? Take this example. I have two materials A and B. I want to etch material A, but not material B.

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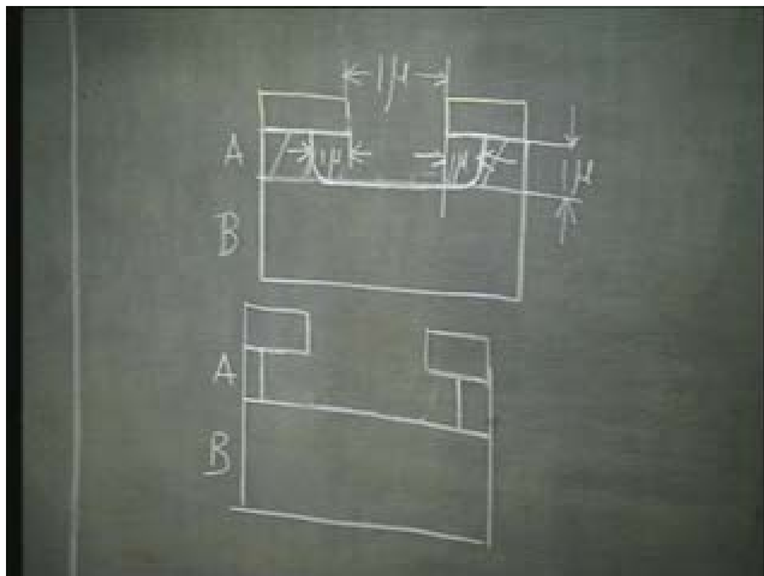

So I want to ensure that when the material B is exposed, when the etching has progressed up to the interface between A and B, the etching automatically stops. That is the etching

system is selective. It etches material A, but does not at all etch material B and of course selectivity, will also be given as the ratio of etch rates of material A and material B, right. So, for any etching system, these are the two figures of merit - anisotropy and selectivity and any chemical etching system for that matter, it will be, it will have quite good selectivity, because some chemical reaction is taking place, right. So, material A is different from material B. Therefore, material A will react with a particular etching material, but material B will not. Therefore you can easily obtain good selectivity when you use chemical etching. But, it is more difficult to obtain anisotropy when you are using a chemical etching system.

So, with this background, let us now investigate what is dry etching all about. Dry etching is also commonly referred to as plasma etching. That is the etching takes place not in a solution, but inside plasma. Now, before telling you what plasma is, let me just digress briefly and tell you that when this dry etching or the plasma etching system was initially introduced, the device dimensions were still not very small. This was sometime in the early 70's, so the fine geometry definition was still not such a very critical problem. At that time dry etching was thought to be a simple alternative to the wet etching. Why simple alternative, because now you can use safe gases instead of corrosive acids. You have already seen that if I want to etch silicon on silicon dioxide, I have to use hydrofluoric acid, nitric acid, corrosive acids; handling them is more hazardous. Instead of that, you can use simple, safe gases. That is one thing.

Secondly after you finish etching, the used etching solutions you have to throw it away. But, since they are corrosive acids, the disposal must be safe. You cannot just throw acid, right; disposal must be taken proper care of. In case of a dry etching system, it is much easier to vent these waste gases and finally it is much simpler to automate. So, actually when you go to mass production, when you want to increase your throughput, you want to increase your production efficiency, then it is very important that the system should be automated. So, these were the concepts with which dry etching was first introduced as a safer and easier to automate alternative to wet chemical etching. But then, as time

progressed and it was found that wet chemical etching has its limitations, it was also seen that dry etching with proper modifications can be adopted to cater to these needs.

Before telling you how exactly these things are achieved in a dry etching system, let us see a dry etching system; let us talk about a dry etching system, first of all. As I told you, dry etching is often loosely referred to as plasma etching. That means we use plasma. What is plasma? Plasma is nothing but partially ionized gas. It is a partially ionized gas. The degree of ionization is fairly low; 1 in 10 to the power of 6 or so and the overall charge neutrality is preserved in this plasma that is the total number of positively and negatively charged particles are the same. So, plasma is a partially ionized gas with equal number of positive and negative charges and the degree of ionization is fairly low that is 1 in 10 to the power 6.

Now, the positive charges in the plasma are ions and the negative charges are electrons. Electrons are very light particles. They have very low mass. So, the energy transfer between the electrons and the plasma that is going to be very inefficient process, right. So, what will happen? Electrons cannot transfer its energy to the plasma. It keeps on accumulating energy. So, in plasma, electrons can really accumulate or acquire very high energy. In other words, the equivalent electron temperature may be very high 10,000 Kelvin or so, while the temperature, actual temperature of the plasma is barely 100 degree centigrade.

Do you understand the implication, what I am trying to say? I am saying that inside the plasma, the electrons have acquired a very high energy which translates in terms of temperature that the equivalent electron temperature is 10,000 Kelvin, whereas the temperature of any material placed in the plasma is going to barely exceed 100 degree centigrade. That means you have realized a high temperature like situation in a low temperature ambience. Now, you know, there are chemical reactions, a lot of chemical reactions, they need a particular temperature to start, right. For example, we said SiCl 4. SiCl 4 will give rise to silicon only at a particular temperature. So normally, without plasma if I have to initiate a reaction, very often I have to raise the temperature. In

plasma now, you do not have to raise the temperature, because the equivalent electron temperature is so high, you can obtain high temperature reactions at a much lower temperature. That is the principle advantage of plasma which is widely utilized in VLSI technology. In case of dry etching also, this property of plasma is made use of. So, this is plasma.

Now, let us see what simple plasma reactor is all about.

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In a simple plasma reactor, what I have is simply two electrodes; maybe, I should separate them out a bit. I have two electrodes, two parallel plate electrodes in a chamber which is held at low pressure. The pressure may vary between 0.01 torr to 1 torr and I apply a high frequency, usually a RF voltage between these two electrodes. So, then the plasma is struck. When I apply an alternating voltage between the two electrodes, plasma is struck; it emits its characteristic glow. For example, nitrogen plasma is going to emit a pink glow. So, plasma is struck. Then, what happens? What really happens inside this plasma?

I told you that plasma actually comprises of positively charged ions and negatively charged electrons and electrons have a much lighter mass. So, electrons are going to diffuse faster to the chamber walls. Let us say, that the chamber walls are insulated. I have a quartz chamber; it is an insulating chamber, so electrons are going to get diffused to the chamber walls. They move faster. The positive ions with their heavy mass, they cannot go so fast. So, effectively what I have is I have the electrons moving towards the chamber walls and the positively charged ions, being concentrated in the middle. So, you see, the plasma potential, which is usually referred to as V with suffix p or the glow potential that is going to be positive with respect to the walls, because it is comprised mostly of the positively charged ions. So, I have a plasma potential here, Vp and I have electrons diffusing towards the wall. So, what is there in between the wall and the center part of the plasma? I have a region which is, which has very few charge carriers. Electrons have diffused to the wall; positively charged ions are in the center of the plasma. So, in between I have a transition region which is like a depletion region, which is depleted of charge carriers.

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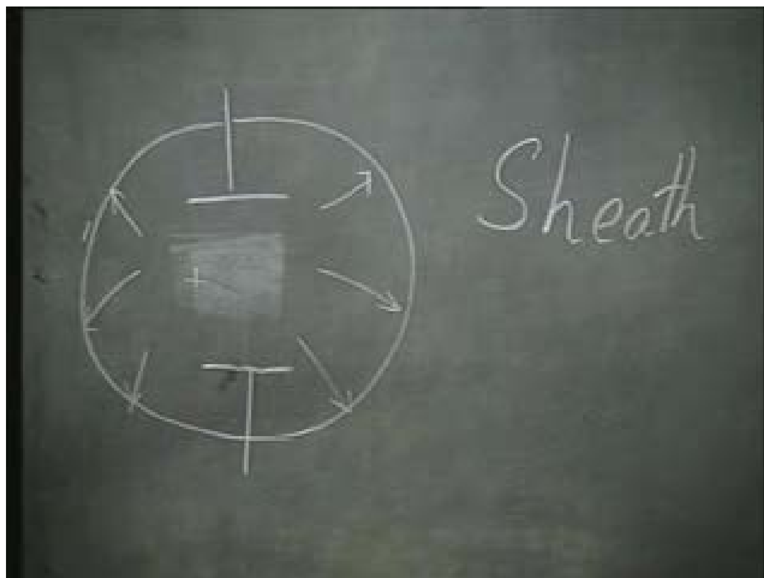

This is called a sheath and most of the voltage that is being applied to the two electrodes, most of it, is dropped across this sheath, because this sheath is the high resistive region; it

is depleted of charges. So, we have a sheath potential. Now, electrons are moving faster and they are going to sit on the insulating walls, so the insulating walls are going to acquire a negative voltage and this process will continue till the insulating walls have reached a stable potential, when any further movement of electrons are repelled. You see, this is negative this is positive. So, the direction of field is like this. It is going to repel any further movement of electrons. Till that situation occurs, I have electrons diffusing to the insulating walls. So, what is, what am I trying to say? I am trying to say that if I place any insulating surface inside the plasma, any insulating surface, then it is eventually going to acquire a negative potential, a stable negative potential, which is called the floating potential. Any insulating surface in the plasma is eventually going to acquire a negative floating potential, right. So, I have introduced the concept of a sheath and a floating potential.

Now, let us for a moment focus our attention on the two electrodes. At the two electrodes situation is completely different from an insulating surface, right; electrodes are conducting surfaces. So, what is happening at the electrodes? I have applied a high frequency voltage, an alternating voltage, right.

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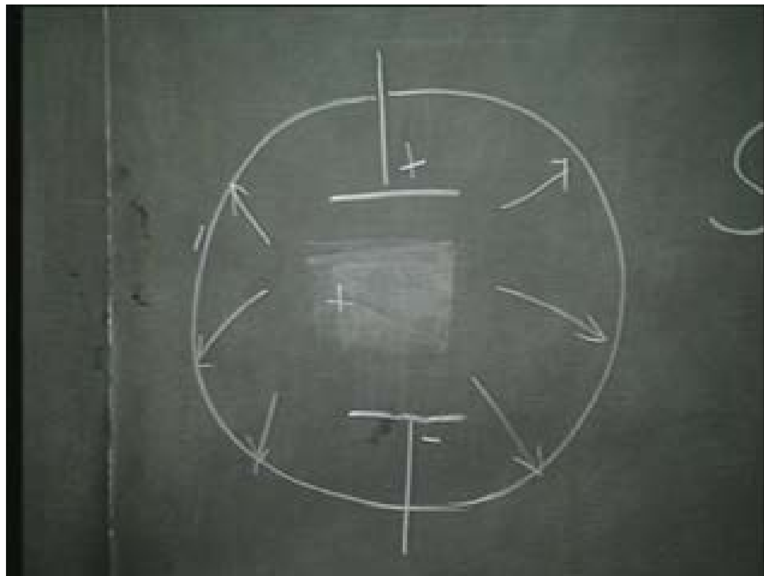

Let us say, during one half cycle one of the electrodes is positive the other electrode is negative. During one half cycle, this is the situation. So, the momentarily positive electrode is going to attract the electrons and electrons have no problem in moving towards that electrode. They have a high mobility; they can keep moving on to the electrode and it is getting replenished from the plasma. So, actually towards the positive electrode I have a high electron current. From the center region of the plasma to the positive electrode, I have an unimpeded flow of electrons, right.

What about the other electrode, the momentarily negative electrode? Well, it is negative; therefore it is going to repel electrons. Electrons cannot come towards it; it does not want to come towards it. Only positive ions can move towards it. But, positive ions are slow to move, right. So, adjacent to this negative electrode, I have a sheath, which is called the cathode sheath, right and this cathode sheath has a large voltage across it. In fact, this will drop most of the applied potential. So, I will have a high voltage drop between the central glow of the plasma and the momentarily negative electrode, which is called the cathode sheath potential and mind you, this is going to determine the ion bombardment energy.

There is a high voltage developed across the cathode sheath. So, I have high electric field there. Under the influence of the electric field, the positive ions are going to be impinging on the momentarily negative electrode. So, the energy with which the ions really bombard on this momentarily negative electrode is going to be determined by the electric field, therefore by the cathode sheath potential, right. So, you see, this situation is going to alternate itself, right. This is during one half cycle; during the other half cycle, the condition at the two electrodes will be exactly different. So, during one half cycle, there will be flow of electrons towards that electrode; during the other half cycle, this electron is going to behave like a capacitor.

In other words, I could say that the equivalent circuit of plasma can be viewed as a diode in parallel with a capacitor.

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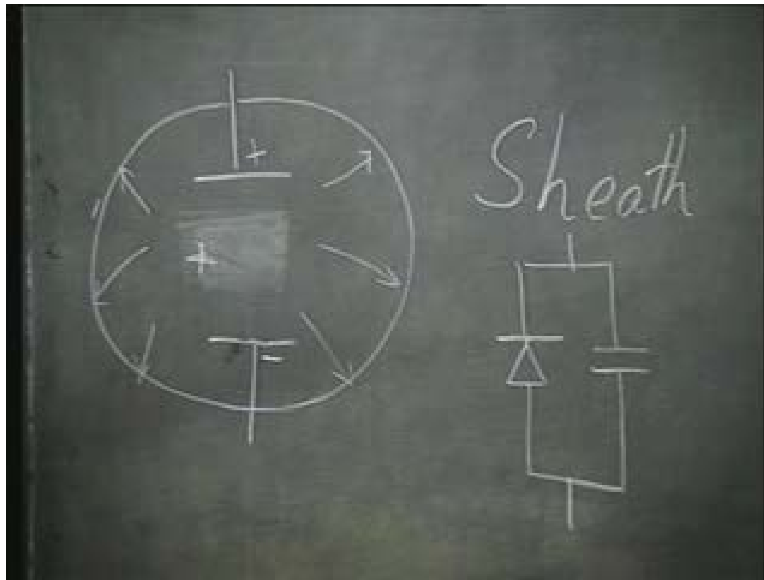

This is the situation towards any electrode. During the positive half cycle, positive with respect to the electrode that is when the electrode is momentarily positive, I have flow of electrons, right; it is like when the diode is forward biased, I have the diode in parallel with the capacitor. When the diode is forward biased I have a flow of current, right. In the negative half cycle that is when the electrode has become negative, it starts repelling the electrons. That means the diode is actually in the reverse bias. Positive ions are slow to move. So, what do I have? I have a positively charged glow, a negatively charged electrode and in between, a region which is deluded of charges that is it is like having a dielectric. So, this is nothing but a capacitor, during the negative half cycle; a capacitor with a voltage developed across it equal to the cathode sheath potential, right. Is the analogy quite clear?

When the electrode is positive, electrons can move towards it. Without any problem I have a conduction current, the diode is conducting. When I have the negative half cycle, electrons cannot move towards that electrode, that negative electrode; therefore, the diode is reverse biased. I do not have a conduction current, because positive ions are slow to move. So, I have actually a displacement current. That is I have a capacitor with a positively charged glow and a negatively charged electrode and with a region depleted of

charge in between which is analogous to having a dielectric in between the two conducting plates, right. So, I could express the equivalent circuit of plasma by simply a diode in parallel with a capacitor.

Now you see, so long as the two electrode areas are the same, the situation is going to be identical to the two electrodes, right. That is during one half cycle, one electrode is going to be positive, the other electrode is going to be negative and in the next half cycle the situation is going to reverse itself. So, over a period of time, I will have the same sheath potential developed across both the capacitors; only they will be 180 degree out of phase with each other, right, agreed, because the situation is identical. So, I will have the same voltage, same sheath capacitance and same sheath voltage, only they will be 180 degree out of phase.

Now, let us assume that one of the capacitors, one of the electrodes has a smaller area.

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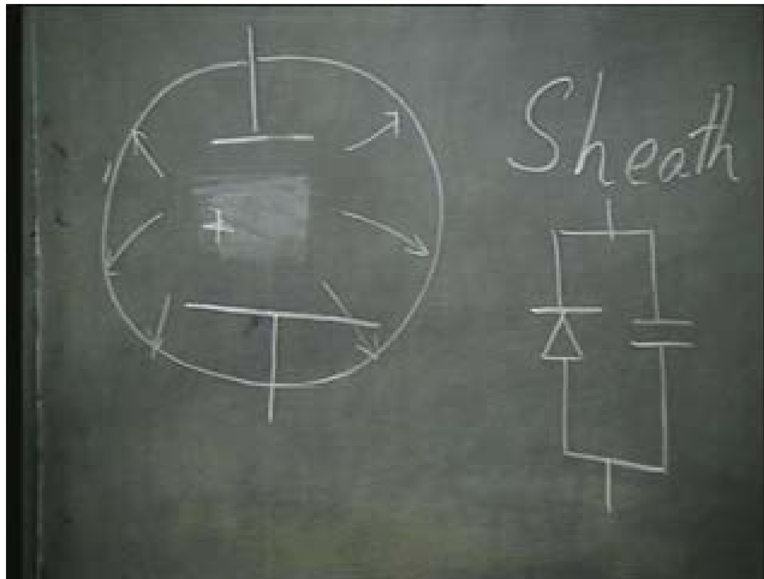

Let us say, I have deliberately made one electrode small and one electrode large. If one electrode has a smaller area, then the sheath capacitance is going to be smaller, because you know capacitance is epsilon A by d. d is the separation between the glow and

electrode, A is the area of the electrode. So, if one electrode area is smaller, the capacitance, the sheath capacitance is going to be correspondingly smaller. So, if the sheath capacitance is correspondingly smaller the impedance is going to be larger, because impedance is 1 by omega C. So, impedance is going to be larger and if the impedance is larger, then the voltage that is developed across that side is going to be more.

So, in practice, therefore you can alter the sheath potential. Therefore, you can alter the electric field towards that particular electrode and you can alter the ion bombardment energy. That is to say if I have one electrode smaller and the other electrode larger, then the voltage developed across that smaller electrode will be much larger, so that the electric field here will be much larger, so that if I have some means of measuring the ion bombardment energy, then the ion bombardment energy will be more. In other words, if I have some substrate placed on this smaller electrode, it will experience a much larger ion bombardment energy. Ion bombardment energy is a key factor in dry etching system. Having varying amount of ion bombardment energy, by varying the ion bombardment energy we can achieve a number of things. We can achieve anisotropy, we can strike a balance between anisotropy and selectivity; all this we are going to discuss a little later.

First of all what I am trying to impress upon you is the reactor geometry. The design of the reactor plays a very important role in deciding the ion bombardment energy. First of all, by now we have clarified two points. One is if you have an insulating surface that insulating surface is always at a small negative potential. Secondly, when you have the conducting surfaces, conducting electrodes, then you are going to have a sheath potential developed across each of these electrodes, 180 degree out of phase. The magnitude of this potential will be dependent on the relative area of the two electrodes, the smaller area electrode having the larger voltage and therefore the larger ion bombardment energy.

In addition to that we have two other parameters to play with. One is the pressure and the other is the frequency. As the pressure is lowered, I told you I will give you a pretty long range actually, that the dry etching is carried out in a chamber which is kept at a pressure

of anywhere between 0.01 torr to 1 torr. Now, in this limit if I keep on lowering the pressure, then the sheath thickness is going to increase, the plasma potential is also going to increase and the ion bombardment energy is also going to increase. So, you see, it makes sense to have the chamber held at a lower pressure, if you want to increase the ion bombardment energy. At the same time, within the limits that is while you are operating the RF region, within the limits if you reduce the frequency, then also the sheath potential will increase and the ion bombardment energy will increase. So, you have quite a number of parameters to adjust when you are carrying out the dry etching. You can use pressure, you can use frequency, you can use the electrode geometry in order to vary the sheath potential and therefore the ion bombardment energy.

Now, usually what is done is this.

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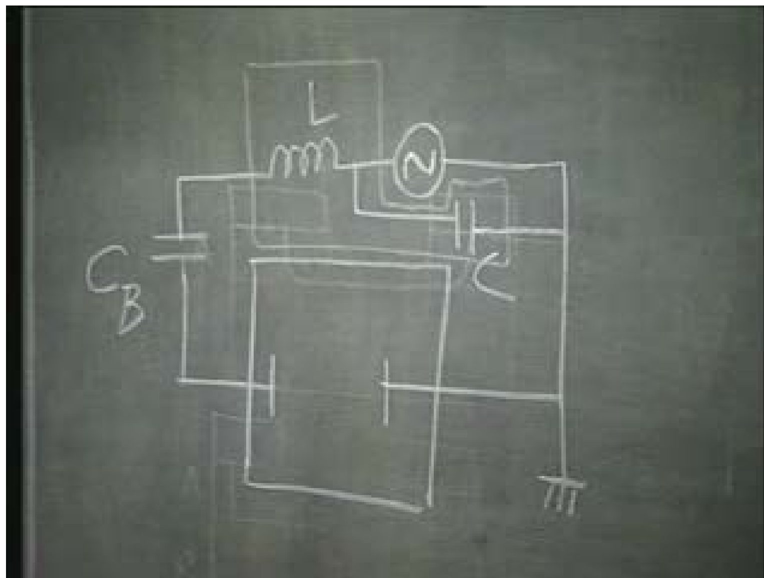

The basic schematic diagram of plasma reactor it is something like this. I have this chamber with one electrode permanently grounded and to the other electrode we apply the RF voltage, so that electrode is positive during one half cycle and negative during the other half cycle with respect to your permanently grounded electrode and then you have a blocking capacitor and then you have your RF network, a matching network RL also.

This is actually your matching network, this LC. This is your matching network in order to minimize the reflected loss. So, essentially what you have is this RF source via a blocking capacitor given to one electrode; the other electrode is permanently grounded. This LC network is simply the matching network, because you want to minimize the deflection loss and if I want to now view the potential that is developed across different regions of the plasma, what is the potential at the anode? We always call this one anode; the grounded electrode is always called anode.

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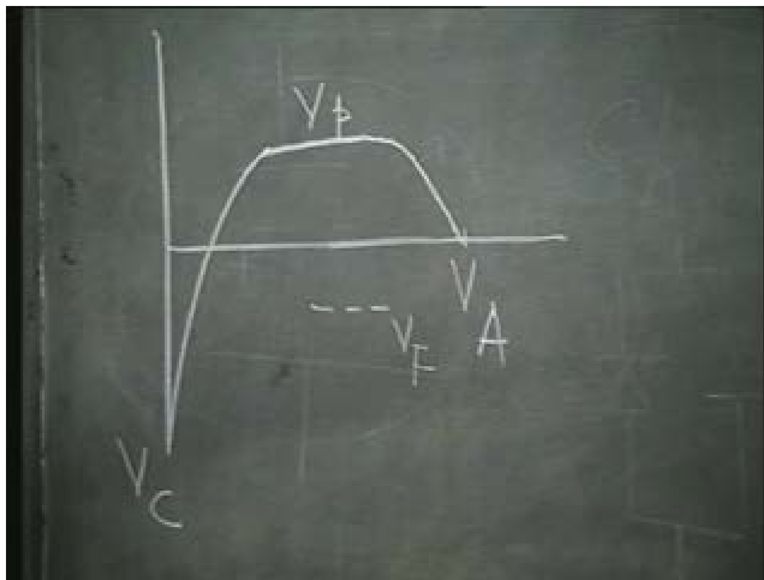

So, at the anode, the potential is always going to be zero, because I have permanently grounded it, right. This is my anode potential, right. I have told you that if I put any insulating surface inside this plasma, it is going to eventually acquire a small negative potential called the floating potential. So, this is the floating potential point, negative with respect to the grounded anode. Any insulating surface you place inside the plasma, it is going to acquire a negative potential. The glow, the central portion of the plasma the potential of which I have referred to as V suffix p that is going to be positive, because it is comprised of positively charged ions. So, from the anode as I move towards cathode, it is actually taking a path like this. Anode is at zero potential, then I have in the central part

of the plasma a potential that is V p, positive potential and then this is my cathode sheath potential V C, a large negative voltage that is developed across the other electrode, right.

So, you see, the ion bombardment will be directly proportional, ion bombardment energy will be directly proportional to the voltage difference between the plasma, V p and the particular surface. The plasma potential is the potential at the center. So, with respect to that center glow potential, if the surface is at a much lower or a much higher potential, accordingly ion bombardment energy will vary, right. So, let us say if your substrates are placed on the anode surface, it is going to experience a small ion bombardment energy, because the difference in energy between V p and V A is not very much; it is a few volts, maximum 10 volts or 20 volts. So, inside the plasma, glow is at a positive potential, anode is at zero potential; the bombardment will be towards the direction of the anode, yes, but with a comparatively smaller energy. If my substrates are placed on an insulating surface inside the plasma the voltage difference is going to be V p minus V F and V F is negative. So, actually the magnitude of this potential is larger. But, even then you know V F is a small negative, fairly. So, V p minus V F is not going to be significantly different from V p minus V A. So, even if you place your substrate on an insulating surface, the ion bombardment energy is going to be relatively less.

However if you place your substrates on this other electrode, your RF powered electrode, which is commonly referred to as the cathode, then since there is a very high negative sheath potential developed between that electrode and the central portion of the plasma, you have a large potential difference and therefore the ion bombardment energy will be very high.

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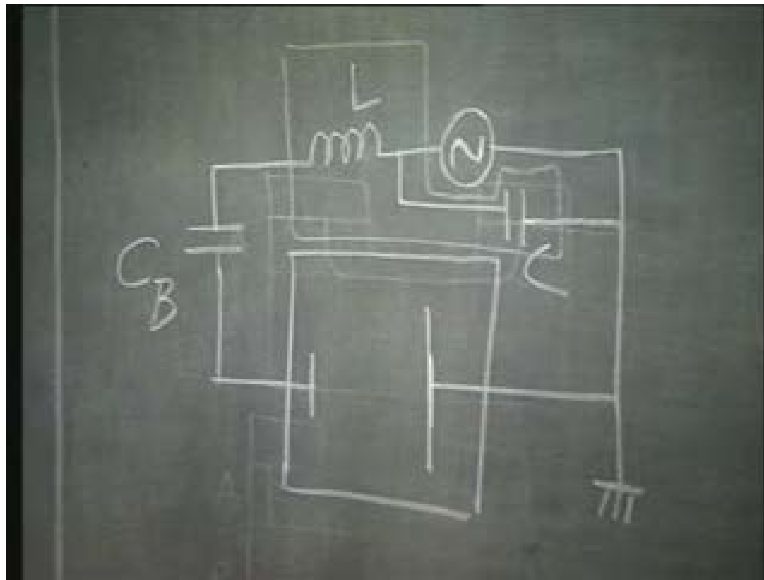

You can further increase this ion bombardment energy by making this electrode smaller compared to other electrode or by lowering the pressure in the chamber or by lowering the frequency of the RF operation. You can obtain a very high ion bombardment energy, right. Why am I harping on this ion bombardment energy? Because, you see, I have introduced the topic of dry etching by telling you that there are certain limitations, limitations of anisotropy in case of wet chemical etching. So obviously, one prime reason for moving towards dry etching is to realize perfectly anisotropic etching and ion bombardment is going to help us in realizing highly anisotropic etching system.

So, in the next class we are going to discuss how exactly in the plasma, etching is done. So far what we have discussed is simply the basic physics of plasma - what is plasma, what are the different potentials in plasma and based on that you know which surface is going to experience what amount of ion bombardment energy. Based on this, now we will see how exactly etching is carried out inside the plasma and then, depending on that how do you design plasma reactor.