Fabrication of Silicon VLSI Circuits using the MOS technology
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Module no 01
Lecture no 25

So we start with the other kind of evaporation which is essentially related to still evaporation but not using heating, resistivity.

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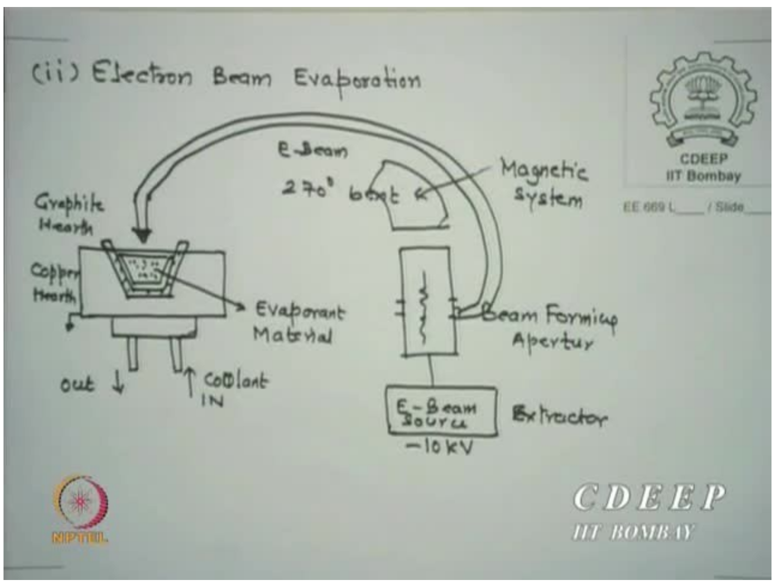

Here is the 2nd possibility of evaporating a material and the process is called electron beam evaporation. The basic idea of electron beam evaporation is the following. I have a some kind of source of electrons which can be from filament. Then you have an extracted voltage, similar like implanter. You have seen the start sources as well as the extractor. Then there is some kind of a in forming aperture which also has some voltages applied on that and bendings are possible. Then this electron beam passes through a magnetic system. Sometimes directly through electric system it is possible if it is only 190 degree shifts but since I want 270, I need both electromagnets as well as electric fields to be bend the beam. Beam bending is essentially because of the (())(1:24).

So accelerated beam, not really very large energy. 10 KeV energy is all that is needed. Typically energy used in electron beam is 5KeV but source normally it can go up to 10 KeV. So this beam, electron beam, some people have electron beam coming from the vertical region itself, the kind of system given in (())(1:49) right side. So I also copied it. That is it. No more, the way I have done it myself was a slightly different version of this. So this electron beam which is accelerated by a potential of 10k and therefore it has a 10 KeV is so focused at 270 degree beam angle that in a crucible which is, which has internally which has a graphite hearth as it is called, you have the material which is you want to operate.

It can be pieces, it can be powder, it can be wires. Anything can be put, there is a crucible there. And of course, there is a possibility of this beam forming aperture. Some voltages are given, so the beam can be scanned as well okay XY. Some vaster can be given on that but normally not needed because this aperture is very small. Once it starts heating this, the energy from the electrons is delivered to the middle or other material and if the temperature rise because of that, it is sufficient enough, it melts and if it is still higher, normally you need some cooling system in this because it is a very large temperature, 1800 degrees centigrade and above.

A huge cooling system and say the outer vessel is of copper, many things, now so this can be replacing the source of either the coil or the basket which are the resistive heater. Same, just only thing now it is a crucible through which material can evaporate. The target is again above, the vacuum is as much as possible because so that the mean free path is larger than the distance and at an angle it will also have the lesser thickness compared with this. To avoid this, as I said, you have a planetary system, the big dome which has a number of vapours attached there which themselves can rotate and whole dome rotates so that uniformity of (())(4:01) thickness is roughly possible. (Perpendicular bhi karte hain, 90 degree mein bhi shift dete hain) let us do perpendicular also, let us give a shift in 90 degree also. But there is an advantage of 270 beam degree (())(4:11) book.

Okay. You know the normally this system, this may be of just just corner of this system. So I do not want to bring anything which may dig us and actually impinge on this. So I want to keep my beam as pure as possible. So if I am pushing from outside, the rest of the system does not affect the heart system. So that is the idea. This E-beam is of course, they are a little costlier system but one biggest advantage of E beam, since it is 10 KeV energy can be provided, it can evaporate many things, not necessarily metals. Of course metals it can, not metals of which are 3000, typically molybdenum, platinum, rhodium, allodium, tungsten, they are not the material which even electron beam can probably melt.

You can, by increasing the energy but then the system will become bigger and whole effort will be waste of money. So here is something you want? There is nothing in that figure. So what is the advantage, disadvantage of this system?

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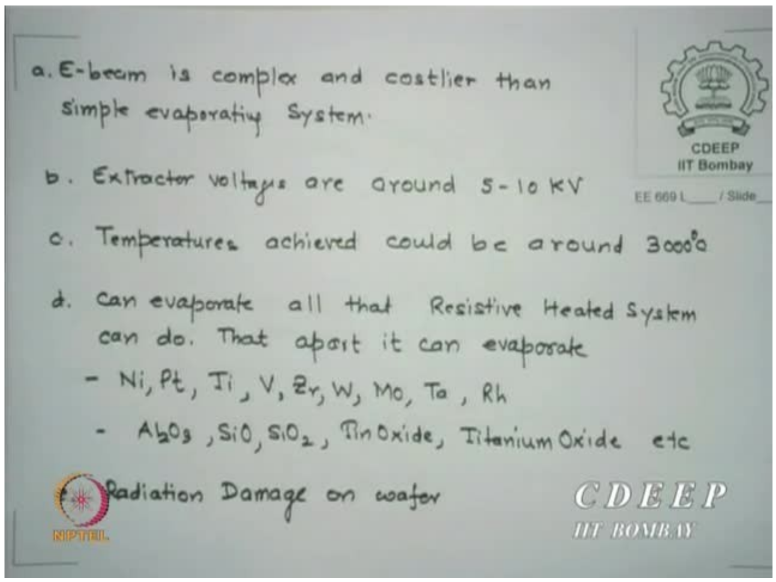

E-beam is a complex and costlier than simple evaporation system. But our system is very cheap comparatively. Indian company can give you as low as 3.5 lakhs or so operator. Whereas if you buy from abroad, any (())(5:41) or anyone, it may cost you 12 to 15 lakhs even otherwise and e-beam maybe even costlier. Typical as I say extracted voltage 5 to 10 KeV each, the temperatures if you increase 10 KeV, some of the temperatures people have reached upto 3000. But typically it should be around 2200 to 2400. Otherwise, the cooling system requires huge amount because if you have a 3000 degree hearth, you need huge cooling and that may cost you.

So people do not make, is possible but normally it is not used for 3000 degrees centigrade heating. Now the advantage being this since it can go higher temperatures, it can evaporate all resistive heated system materials and that apart, it can also evaporate nickel, platinum, titanium, vanadium, zirconium, tungsten if it goes to 3000. Tungsten, tantalum, rhodium, allodium, einsinium, everything. It can also evaporate of course depends on the if you have 10keV normally most beams are 5 KeV, then there is of course higher materials will not be able to evaporate.

You can also evaporate Alumina, SiO, SiO2, iron oxide, titanium oxide, and many other such oxides. The major problem with electron beam is, since it is 5KeV, even if you are now saying that electrons are only heatting the crucible, one believes that electrons do not disperse but in real life, they may scatter from variety of parts of the system itself, from the crucible edge, from the edge of the where the magnet hits out. So all beams are not fully focused though we try, some is scattering, some is secondary electrons reached. Now these, some of these electrons can go and hit target.

Now any high-energy beam or high-energy electrons, if they hit at least an MOS device in particular, it may actually charge the MOS. That means, the oxide charge will increase or the -charge will increase which essentially means threshold will shift. So it is called radiation damage. So 5 KeV is a small energy, the radiation damage in space is much more higher. There is a NeV energy charged particles are there in space (())(8:16) but even 5KeV but the distance here is very low and therefore there is a damage and the 1st, our effort to study this electron beam damage was in 1987-88 and one of my B tech students did India's 1st radiation damage studies so just to tell you because he is now with cadence, nothing to do with evaporations. Cadence US, he is a manager in some group. So this radiation damage was our great project. We did from 87 to 93. We developed a new technology for radiation harness but all said and done, our 1st effort was on electron beam damage. We just wanted to see how much damage it gives and to a great surprise, because our oxides are not that good, compared those days, in 80s, our damage was sufficiently high. We used to see huge (())(9:13). So we 1st realised that just charging is happening. Charging is happening.

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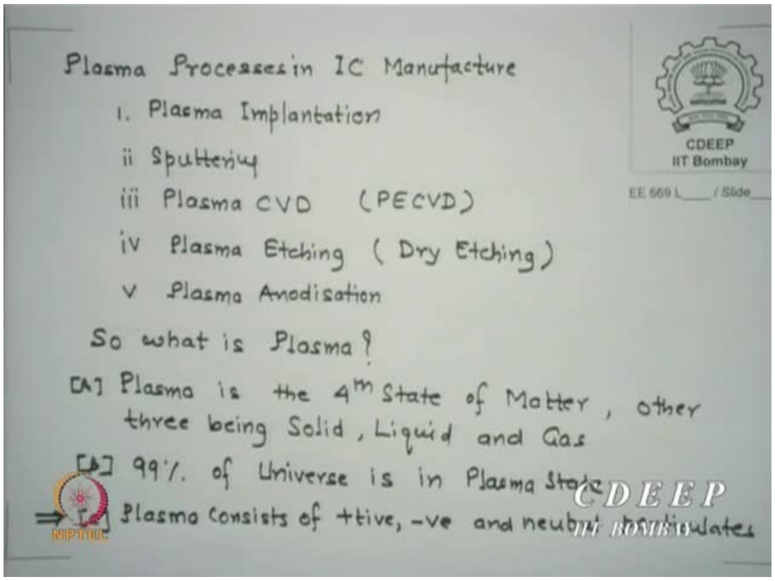

The next possible process in which we can do evaporation but many other things is to use of a plasma in IC manufacturing. You look at the list again, there may be many more. I did not add everything. One of the features of plasma processing and IC is that you have what is called as plasma implantation. Sputtering essentially is based on plasma process. You can also deposit any material using CVD which is plasma enhanced CVD. You can always etch any material using plasma and there is no liquid there and therefore it is called dry etching. Of course in dry also, there can be reactive and non-reactive etching but essentially plasma etching and of course one can do anodisation of silicon itself using plasmas.

So you can (())(10:20) oxide using plasma anodisation. The problem is plasma is similar. If it heats too much to a high-energy, then it may actually create damage but most plasma damages can be annealed in the plasma itself. That is the fun part, think of it as (())(10:37) plasma itself can anneal the much of the damage. So what is plasma? Plasma is the fore state of matter which is very, I mean not so much taught from 1st standard. We keep saying 3 states of matter, solid, liquid, gases. But in fact, 99 percent of the universe is in this state, that is called plasma state and we hardly talk about it. That is a interesting thing. What is plasma? Well, it consists of it is please take it always, plasma is charged neutral. This has to be understood.

Plasma is charged neutral. So there will be electrons, there will be ions, there will be neutrals but net charge is 0. Okay. Charge neutrality holds even if there is negative charge, positive charge and neutrals. This has to be understood. There are all this this is something which people do not realise but this has to be understood that plasma is still neutral.

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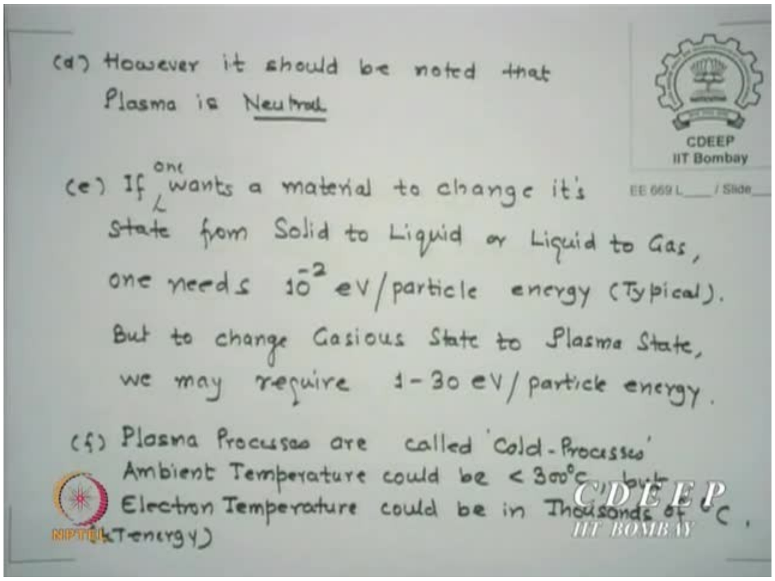

However, it should be noted as I said, plasma is neutral. If we want a material to change its state, U or V, I forgot that or maybe. If one wants a material to change its state from solid to liquid or liquid to gas, actually energy required is very small. 10 milli electron volt. 10 milli or 10 to the power - 2 electron volt per particle. So a very small energy is required to liquefy solid to liquid and liquid to gas but if you want to convert gas is plasma, then you need roughly 1 to 30 electron volt per particle energy to actually create a plasma.

So plasma creation is much higher energy requirement compared to conversion from solid to liquid or liquid to gas. Is that point clear that why plasmas are not so very common? Because you will require higher energy per particle to create plasmas. Why are we so keen about plasmas? I have already listed that. All processes which we now going to do next few days, all are plasma-based. So today probably I wish to actually tell you what is a plasma, why it is so crucial okay and what is the funda issue on that. Once you understand plasma, then you can think designs of plasma systems are understood.

Another issue which plasma avoids you is called cold processes. The ambient temperature can be even as low as room temperature or at best less than 300, 250, 200 degrees centigrade. So it is a cold process. But we are said the temperature it gives is how much? It can give to 3000 + which means somewhere energy must be provided. Even if the ambient temperature is not large, the energy is higher, which means KT is higher means T which is called electron temperature is 10 to the power 5 10 to the power 4 degrees centigrade. So it is the electron temperature which we are rising and not the ambient temperature.

This is the difference between normal procedure which is like diffusion. What we do 800 degree furnace, 1200 degree furnace. There is nothing called 1200. This everything is below 300 but internally, there is a huge energy provided which rises the temperature, electron temperature to 10 to the power or 10 to the power 5 and it can create therefore thousands of degrees centigrade of temperatures. So that is how the plasmas have become very popular. In all other diffusion process, implant process, we say anneal or any temperature time cycle, what does it do? What did it do? Is it driven the impurities from its original implant position or diffusion.

That means profile changes. All your circuit analysis was based on a given profile. Okay. Now we all must plan all of that apriory. Now that means any process which I do later should be such that it should not actually affect the process which earlier I have done. Which means the temperature should be as low, in plant, I did anneal 800 but then, I will never go beyond 800 and now I will have always be less than. So DT product at 300 degree is so small, 10 to the power - 16 - 17 into T is the DT. So you can say practically nothing changes at room, these temperatures.

So therefore these are called cold processes. They do not change any profiles or there is no annealing going on. There is only localised heating going on and you are doing whatever you otherwise would have wanted to do okay. So that is why plasmas are very very important that they give you cold systems but a very high temperature increase possibility. Is that okay, all of you? KT. KT is the energy. T is increasing. No, it will not. Plasmas are take from me once for all, plasmas are neutral.

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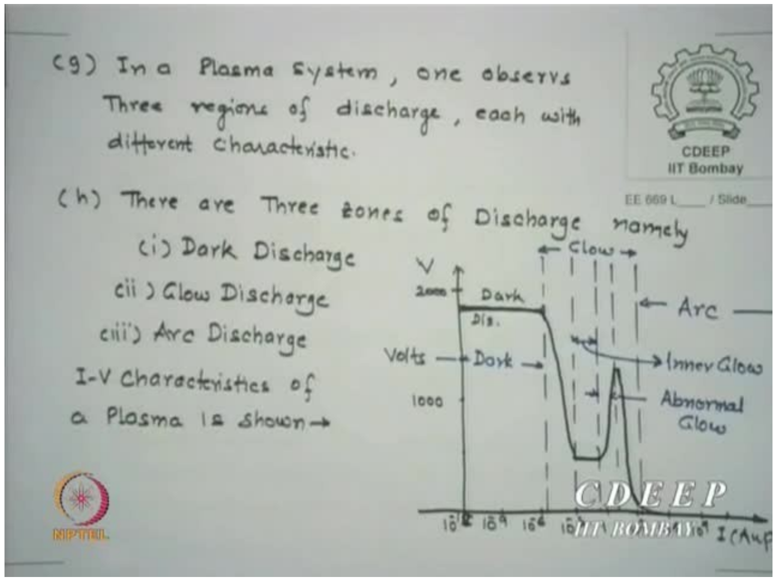

If they start charging the whole, you will get a shock of your life. So please never think. No system is chargeable.It must provide some ground sometimes. Otherwise also it will create a neutrality. Like semiconductors, you put voltage (())(16:25) MOS capacitor will not charge you enough. Okay. Then charge neutrality always holds. It is locally we may say space charge but still N and P are same. N + ND P + ND is N + NA. As in semiconductor, charge neutrality holds. This is important. All analysis is based only on this.

For a transient case, there may be a possibility what you are thinking but these cases are steady-state. So we are not thing into it. In transient, many things can happen. There are reversible processes, there are non-reversible processes. So we will not discuss that. We want specially another hours for (())(17:10) transient processes. KT. K is 1.23 10 to the power - 23. Dus KeV ko isse add karo - 23. Kitta temperature jaa sakta hai? Energy to KeV me hi de rahe hai na? 10 KeV ka to extractor laga diya na. but tees EE ke energy me hi itna temperature hai. Divide karo na K say. Electron temperature to bahut zyada hai (())(17:33).

There are 3 zones of discharge in a normal plasma system and this is called the IV characteristics. So plasma, you draw it and then I will discuss. Is a very important, this is the fundamental of plasma. Where do you use plasma very often? Tube light. Of course, this is the figure given probably in plamer as well or maybe any anything you want Google, this figure is most common. IV characteristics of plasma is the most common figure available in with associated plasma. I is in amps, V is in volts, the scale is 0 to 2000 and it is 10 to the power - 8 or - 7 to + 10 to the power 9 or 10 to the power 12 amps, huge scale.

These are log scales, shown on a log scale. Can be made (())(18:29). That means all energy is not imparted. As I said, the net energy I pushed is not received by this. This is a energy conservation. So not energy will be delivered. So not all temperature will rise to 10 to the power 4. Is that clear? Energy is proportional to KT. Is that correct? So T will rise definitely the energy but all energy is not transferred to the material. This has to be understood. There is exchange. Mass, both energy and momentum have to be conserved. So not all energy is transferred.

So there are 3 zones of discharge of a gas, okay I should have forgot, I did not write. This is a, plasma is only created from a gas. Gas to plasma state, okay. So we are now looking for dark discharge, glow discharge and arc discharge. There are 3 zones in a plasma. So if you look at the 1st part okay, around 10 to the power 1 microamps or so current, I do not see any plasma. It is called dark. Dark means no plasma. So all dark zones are called plasma free zones. So there may be ions but there may not be electrons. Is that point clear?

There may be ions there but there are not enough electrons. Only when electrons and ions come together, there is some light is seen. That is called glow. Dark zones are (())(20:03) where there are no free electrons to interact okay. So this initial region is called dark region. Okay. So let me come back, I will just show you. From safeties onwards to something like thousand amps, there is a region which is essentially called glow region where plasma exists. Glow is most important for us, glow. And in glow also, there are some peculiar things we are seeing, in some part is called normal flow, the other is called abnormal glow.

Why I showed you this specific abnormal glow? Because only this region is what is used in IC fabrication. So call this abnormal zone which does actually it show up always something like this, normally okay. It did not. Somewhere, it peaked up again and this is the zone where I is high and V is high is essentially what is of in a glow is of interest to us. That is the whole plasma processing rest on only this zone called abnormal glow. Higher of this, we find the volt, so much charge is inside the tube or inside the area, the conductivity falls drastically. So the voltage becomes very very low but the currents are extremely high and there you actually see arcs.

If you have air and you just apply 30 volts, bring it close, it will spark. Spark in an arc discharge. Okay. Is that clear? But that is essentially people believe it is air. Actually air molecules do not break so easily. It is the moisture which actually picks up the arc okay. So you must remember, it is the moisture which actually arcs out okay. So anyway, so these are again we are, I repeat, my only interest within this zone for all IC processing, in the glow region also, I am more interested in something not (())(22:14) abnormal. I do not want normal glow. I want abnormal glow and only this region I may prefer to work on. So all my processing should be maintained somewhere to create abnormal glows.

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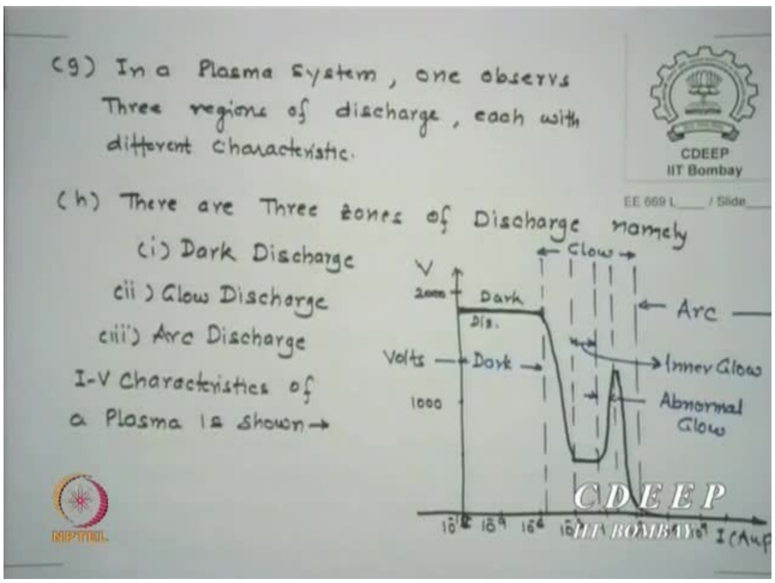

Now let us, this I said it, so I now show, of course the upper figure right now you do not look at it. That I repeat again. If I apply a voltage in a tube or in a system across two ends, so applied electric field. Is that clear? So there is a gas. I apply a voltage across. If the supply voltage is larger than the breakdown voltage, what is breakdown I defined? Breakdown is the voltage at which electrons start ionising the gas ions. So if electrons and ions start forming, that is called breakdown. So, onset, breakdown is not total.

Onset of plasma is called breakdown voltage. So if your applied voltage is larger, so what will be the dark region? Then your plasma has not been initiated. Is that correct? Plasma has not been, so your voltages are looks higher but not sufficient carriers have made available to you and therefore there is no plasma onset. Okay. That region is called dark region. No onset of plasmas.

Electrons are emitted at cathode now you can see if I apply cathode one where is a negative potential and the other is a positive, so cathode is negative potential. So electrons are emitted from cathode because opposite polarity carriers will go towards anode.

Some way, this figure can be seen but there are many other things shown there. We will discuss them separately. This is my cathode, this is my anode. Electrons will travel towards anode. Is that correct? This figure you do not draw now because we will come back to draw that. I wrongfully draw here thinking that I may not give you this but then I decided to write. That figure was anyways (())(24:29). Now if you electrons emitted at cathode travel to anode under a fixed ionic collision. Now you can see here. I have a gas, some electrons struck and ions are created.

Which side ions will try to move? Towards cathode? Electrons will travel towards anode. This has to be understood okay. Now, is that okay? So last line I start now. Electrons emitted at cathode travel towards anode and at fixed ionic regions, then such created ions travel towards cathode. Because they are positively charged, so they travel towards cathode.

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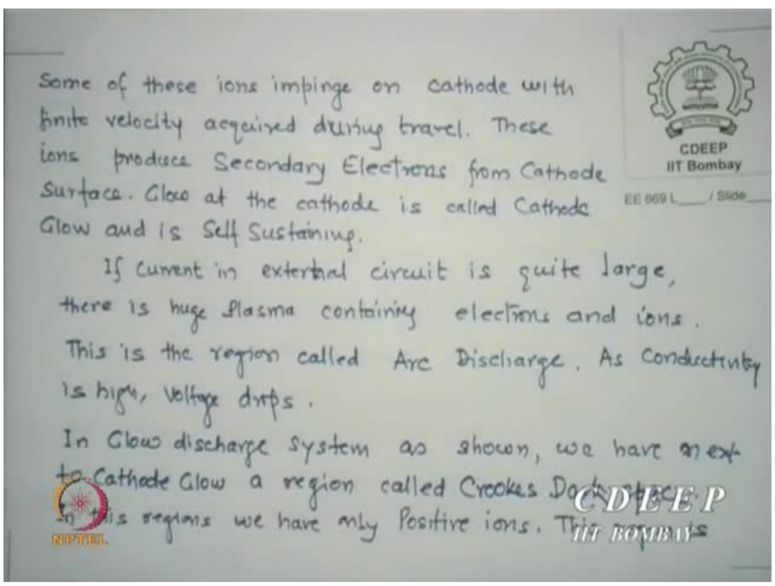

Some of these ions, when they travel, what is the force on them to travel? The electric field which I applied, that electric field which I applied. So they pick up energy. Any charge carrier going through electric field will pick up energy. How much is that? Q into V. So charge into voltage is the energy. And what is the force? Q into electric field is the force on that. Q is not electron charge, now ion charge. So these energy is larger. Is that correct? These ions come and hit the cathode, they have energy (())(26:01), so it will also ionise that region or something and it will create what we call as secondary electrons.

One electron was anyway coming because cathode is releasing electrons going towards anode but this impinge also will create continuous energy and when it will lose energy, it will create electrons and these are called secondary electrons. These ions produce secondary electrons from cathode surface. Glow at this cathode is called cathode glow. Why? Now there is ions, neutrals, electrons. Anything possible. So near cathode, very thin region, you actually have a glow. So if you see actually tube and it starts, the cathode becomes slightly violet and then suddenly it loses that because then once sustained, it does not need that. So this is called cathode glow.

But now thing what is happening and this is self-sustaining. Ions will come, electrons will come out and some steady-state will reach, so you will have a constant cathode, thin cathode glow. We apply voltage. Some ions will lose, some new ions, some new electrons will go, again ions, so average and please remember again plasma is neutral. Please never go against that. Is that clear? This (())(27:29) impinging in on him. If the current in the external circuit is now large let us say because we have ions, that region has now larger conductivity.

Or you increase the voltage outside. Then you have a huge plasma, electrons and ions and this region is called , sorry this was wrongfully put here. This sorry is (())(28:00). This was something which was we said, dark discharge, glow discharge and this the arc discharge. In arc discharge, if you apply a large currents and large voltages, air or whatever gas will breakdown instantaneously and that is called arc discharge. Okay forget about this. I am sorry. You come from here. I do not do how this, I wrote here but anyway. In glow discharge system, I have shown you how.

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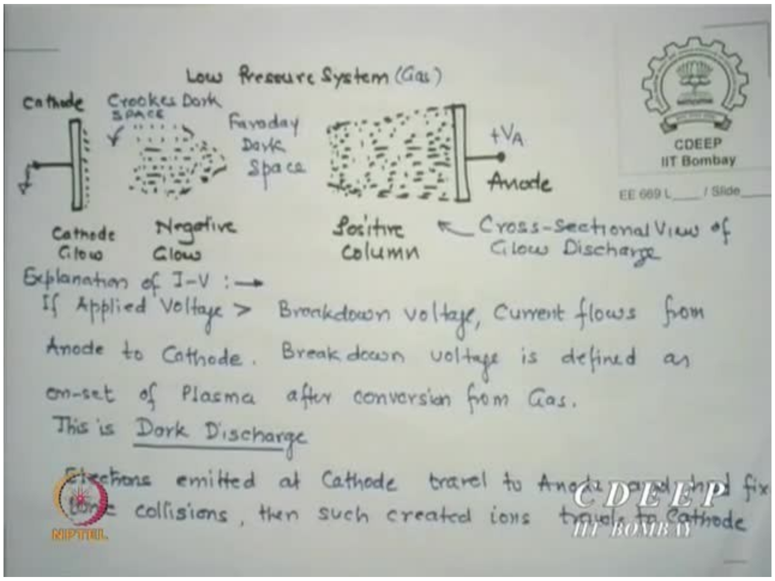

Now this is some now you draw this now you look back to this figure which is most important okay. This has a low-pressure gas in a chamber. Okay? It can be even tube, cathode wire tube. It can be anything. All in a system which is evacuated. So I have a cathode, I have a anode, I apply the voltage positive with respect to cathode. So electrons start coming and this as I say, some ions strike cathode and make it a glow there which is thin glow but is called cathode glow. However, there is a space in which there is no collisions.

What is? This is because of I have written down below but can be what? Can you think? This region between the ionic region or glow region, there is a gap between cathode glow or cathode to this region and which is called crookes dark space. That is why, S is always written by me. Crookes, his name is Crookes. This occurs because electrons now this is you think of it why I suddenly thought of this. What was the word written above? What does improve? Mean free path. Yahan se yahan, mean free path hai. So no collisions. Is that clear to you? So if the distance from the cathode to the next glow, electrons do not interact with ions okay because they have the mean free path okay.

Once they reach that mean free path, now they see gas and now they see ions and they may and by then they might have already acquired sufficient energy and plasma can be created. Is that what clear? So what is Crookes dark space? It is essentially the mean fa mean free path distance from cathode where no collisions are possible. This Crookes dark space is very important, is also called, there is a voltage drop across it. Why voltage drop? It has no ions there okay, only electrons and so smaller conductivity.

So there is a voltage drop there. It is called cathode fall or potential across this is called cathode fall and that potential, that region is also in our plasma system is called sheath, S H E A T H, Sheath. This Crookes space is called sheath. So there is a sheath potential. Is that clear to you? Every sheath and what is in sheath? There are no ions there. Is that clear? Electrons are now traversing in the mean free path. Ions are yet to reach this. So secondary electrons, main electrons, both are not able to interact and they travel.

That small region shown larger just to show (())(31:39) but it is a very closed mean free path, maybe a few centimetres and therefore you see a dark space there which is called Crookes dark space. Okay. In this region, there may be positive ions but there are no electrons which can interact. Okay. So there is no electrons and ions, then there is no glow. Is that word clear to you? Is there are no electrons and ions together, plasma what did I define plasma? Equal number of electrons, ions and possibly some neutrals is plasma.

If electrons cannot interact, they move out. So in that region, there is ions but they are not interacting with electrons. So this is a case where there is no glow. How much it can be, the length of the mean free path of the electron, that region is called Crookes dark space or later, we defined the space as sheath . Okay.

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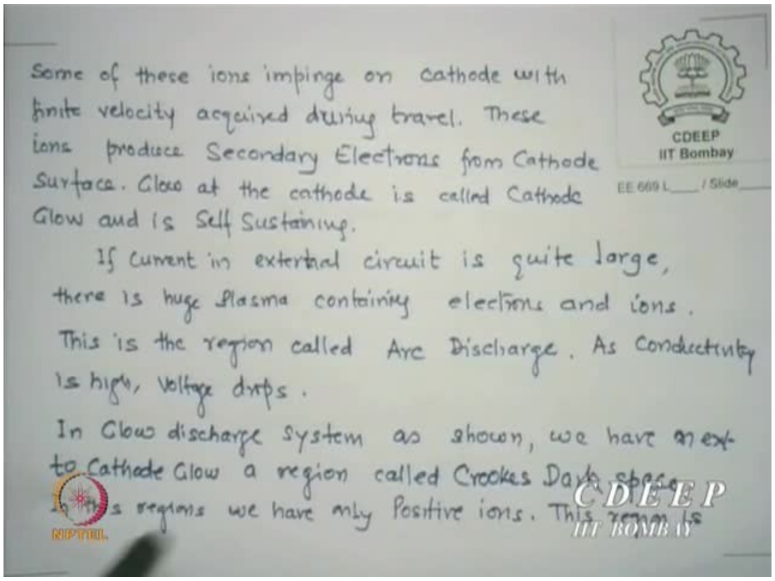

So in a glow discharge system, as we annex to cathode glow, a region called Crookes dark space is in this region, we have only okay phir se likho, likh diya maine. In this region, there are only positive ions and no electrons. Is that correct? There have only positive ions but no electrons. So no plasma. You just, I this last ye jo beech ka para hai na, wo pehle IV ke saath jod dijiye. Please remember, this in between part, arc discharge part be part of IV. Wo glati se idhar likh diya maine pata nahi. Maybe in some mood, I wrote that but I just want to clarify. So we are now looking into this figure, essentially this figure from here.

So cathode fall hai thoda sa cathode ka glow hai. wo minor rehta hai actually because most of the electrons are living that place. So the why it is very small? Because most of the electrons from cathode leave, 2nd electrons leave but some electrons are coming, some ions are reaching. So some glow is possible. Okay. So is that Crookes space is clear? Let us (())(33:51) further. And this is a very important region for us, this is the most important region for us. This is called sheath, okay, S H E A T H. This Crookes dark space region is called sheath which is where is that? It is always close to cathode okay, very close to cathode.

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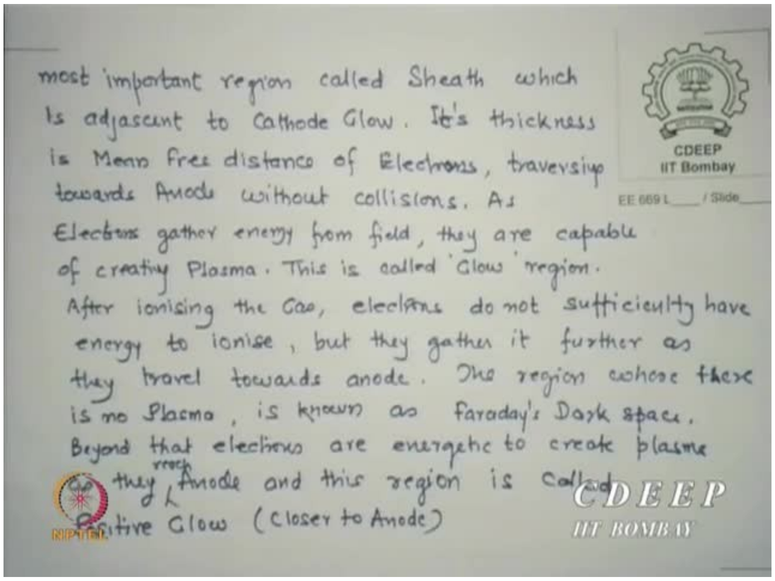

And again I repeatedly saying it, once again I say, its thickness is roughly the mean free distance of electrons traversing towards anode without collisions. Is that correct? That is a typical dark space will be. However, as it crosses the mean free path, there was still electric field applied. So what will happen to these electrons? They will further accelerate. Energy is applied, you are applying a field. They will get forced and they will pick up the energy. As electrons gather energy from the field, they are capable now to interact with plasma.

Please remember, when ionisation can take place at least few eV per particle energy is given back as the plasma requirement. Is that correct? So till these electrons are able to get that much energy, you cannot create plasma. Is that clear? So it interacts with ions and creates plasma okay and this is the glow region. Once it interacts, ions and electrons available to you, this region is again, which region? Glow region. And among these 2, among the glow region, I said there are 2 possible glow regions. One is normal, the other is abnormal but that will wait okay. Okay, after ionising the gas, electrons do not sufficiently have energy.

Once you, why they lose energy? Because they have spent their energy in ionisation. But there are still travelling towards anode. So what will happen? The electrons which will come out at this glow, will not be having enough energy. Is that, they have lost energy no, that is why they created ions. As they come out, since they have no energy, they cannot ionise. Is that clear? So just a minute, I will just show you a figure.

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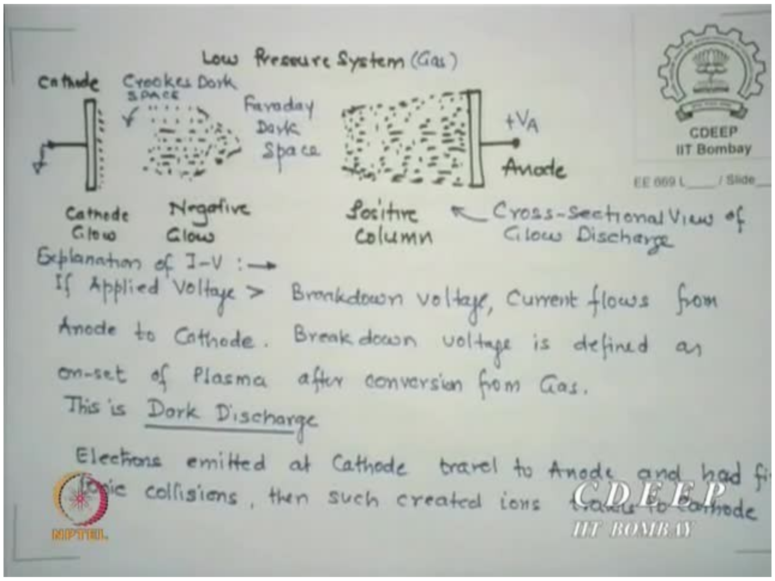

As they come out of this plasma, beyond this, the electrons do not have sufficient energy to ionise okay. They will pick up now but still, they are so they will travel for some distance before they acquire sufficient energy again and start ionising. Is that clear? This gap between this glow and this glow given the name Faraday's dark space. Is that correct? The person who is our maai baap. If Faraday would not have been there, probably electrical engineering would not have been there. You would have been saved. So this Faraday's dark space actually Faraday did this experiment. The name was given later. Faraday was also looking for discharge.

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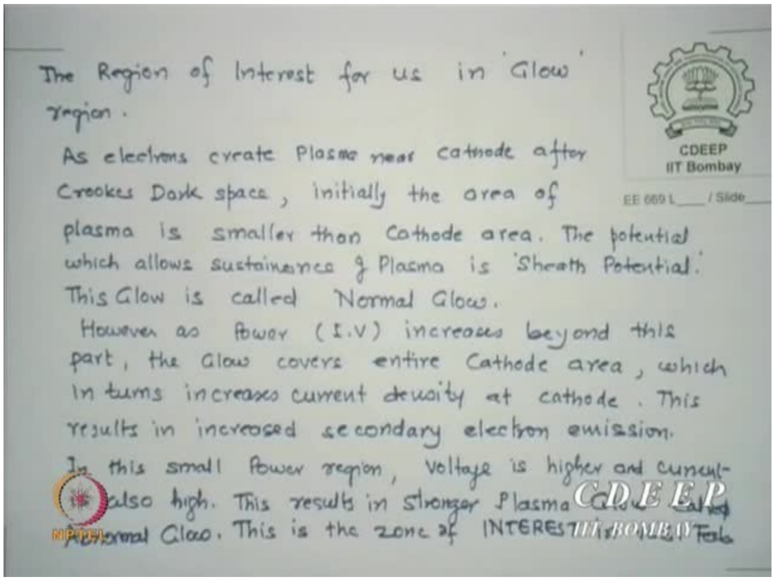

The potential which allows sustenance of plasma after ionising the gas electrons do not have sufficient energy to create further ionisation. So some part is left dark which is called Faraday's dark space. Beyond that, electrons, now they are closer to anode. So they are very highly energetic to create plasma as they reach anode and this region is called positive glow. The word is positive and the earlier we said negative is because of what? Glow is neutral. So why it was given name negative, positive? Closer to cathode, negative glow, closer to anode, positive glow. No other difference. Fir se bata dete hain. Neutral hai wo. The glow closer to cathode was given a name negative glow, closer to anode is given positive glow.

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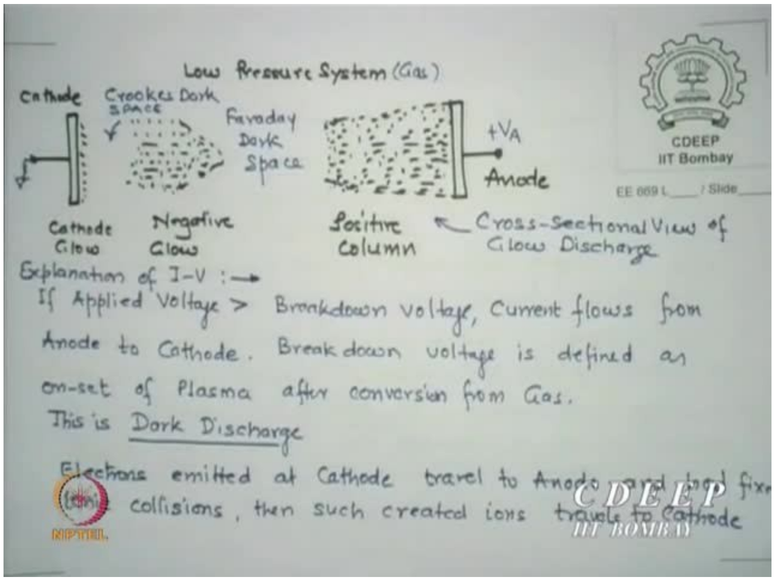

Now there is something which I wanted to tell you about the if you have written down this is what has happened now overall. I have a cathode fall or cathode glow, Crookes dark space which I call sheath. Then there is a negative glow, then there is a Faraday dark then there is a positive column towards anode. Okay, this is essentially a cross-sectional view of the plasma. So let us now do is that okay? All of you? This is what we are shown, drawn the figure, I am just trying to say how much what is so far we talked about. I do not know where is this figure but maybe (()) (38:33).

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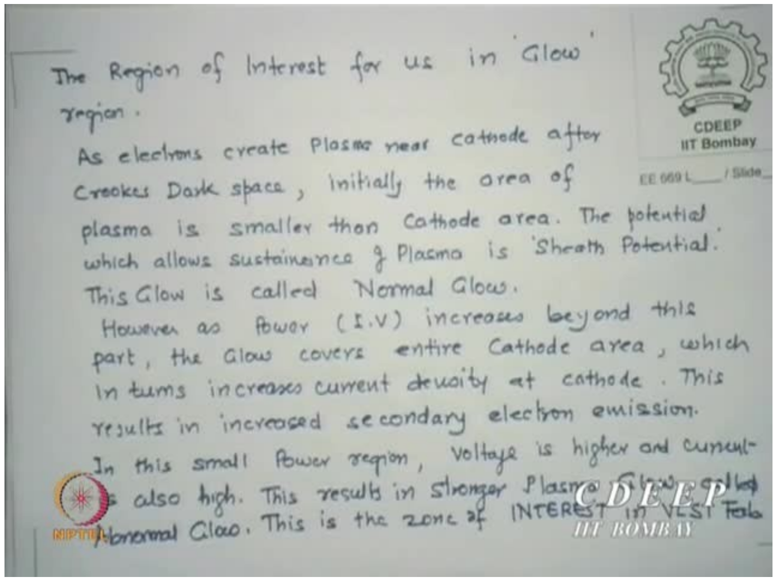

So as I said earlier, the region of interest to VLSI people is not really all dark spaces or non-dark spaces or glow. Only glow region near cathode region is of interest to me inside. Only glow region closer to cathode is of interest to me. Is that correct? As electrons create plasma near cathode after Crookes dark space, initially the area of plasma because pure electrons are coming and the interact with ions, so the area of the plasma is smaller than the available cathode area. I repeat. Of course there is slightly (())(39:12) ye area jo hai comparatively is smaller than the initially that area is smaller because electrons aa rahe hain, ionize hota jaa raha hai.

So initially area is smaller as you start getting a glow. Now this is an issue electrons (())(39:34) the potential which allows sustenance of plasma is the sheath potential and this glow is called normal glow. kitna potential hai cathode ke wahan par? Sheath potential. Aur wahan jo glow hai, wo normal glow bolte hai, initial jo glow hota hai wo usko bolte hain normal glow. However, in case I increase the power, aapne IV characteristics dekha na? I increase the current okay. So if I increase the Power now, that is IV product, beyond this where it started, why what will happen if I increase electron current, I mean current means externally?

The number of electrons I am emitting will increase. So ionisation will be stronger. So finally, the total glow area will be same as that of cathode. So initially glow area se fir wo voltage jo hai kyunke initially kya tha? Plasma bana. Ab jab ab badhate jaa rahe hain. Current badha to net resistivity badh gayi. Toh voltage drop shuru ho gaya. But as it starts ionising again heavily, it starts falling down once again. So initial glow se neeche aaya, fir till the time the new ionisation starts, the resistance starts increasing in the system, so voltage starts rising but at certain potential, ionisation is very heavy. It falls down again and that region where it initially starts rising and falls down again, it is called abnormal glow region.

However, as power increases which in turn increases the current density at cathode, this results in increased secondary electron emission. In this small power region, the voltage is higher and current is also high. This results in a stronger plasma creation than and finally resistance goes down or the current goes down and this region is stronger plasma region is called abnormal region. And please take it, this is the only region of interest for me. To uska kya meaning hai? Higher current density pe mujhe operate karna padega yadi I want abnormal glow. Of course we further increase current kya hoga? Arc discharge shuru ho jayega.

Currents are very high but the voltage is because why these ions are so many? So the voltage drop becomes very low and almost huge amount of current flows. 10 to the power 9 amps ka current jahan pe. Arc mein, currents can be as high as the power 9 amps. So please do not, that is why shock aata hai bohot baar yadi aap arc mein kahin aa gaye toh upar jaa sakte hain. So arc ke saath kabhi khelne ka nahi. Okay. So please remember, this is the most crucial part to understand in plasma that after all that, I only have a gas, I will apply a voltage, I will ionise it and see to it, I am in a normally region which is of my interest which is abnormal glow. Abhi thoda aur jo actual system mein we will do little more mischief. Here is some more mischief for you. Ho gaya kareeb everyone?

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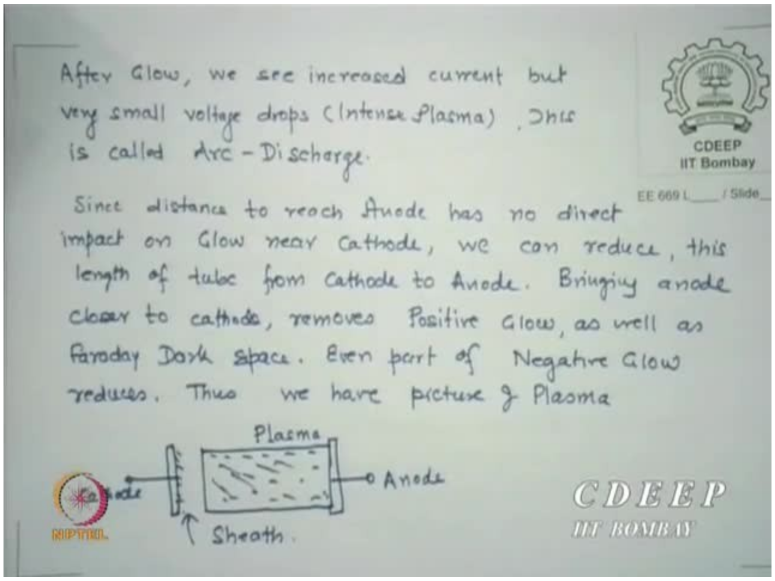

Of course, as I said, after that this glow, if you further increase current, arc will start but that is not very important. Since the distance to anode, to reach anode wo kitne jaa ke anode pahunchte usse sheath ke potential pe koi farak padta hai kya? Negative glow pe bhi koi farak nahi padta hai. Is that clear? So how (())(43:38) has nothing to do with the cathode region. Is that clear? Ions hai, wo hit kiya, mean free path jitna hai utna space hai beechme. wahan plasma hai. Is that clear? So abhi wo bohot zaroori nahi hai ke wo anode ko bohot door rakhenge. (())(43:55) dark space dikh hi jaye . hum hamara use koi sambandh nahi hai. So let us do what further I say.

Since distance though to reach anode has no direct impact on glow in your cathode, we can reduce this length of the tube of distance from cathode to anode bringing anode closer to cathode. You bring your cathode closer to anode. So sabse pehle toh wo positive glow chala jayega. Aur chhota karenge toh dark space Faraday bhi chale jayega aur part of the negative glow mein (())(44:29) if you bring too close. But that is fine. Even part of negative glow reduces, this will have a picture of plasma of this kind. Abhi dekha this is what it will look like.

If I reduce the distance between anode and therefore, then I may have a plasma touched to anode okay. And this may be negative because negative glow, now it cannot be called negative also because it is also positive as well as negative. But negative glow bhi kam ho jata hai, part of this. And what is in between this plasma and the cathode? Sheath and what is the importance of the sheath? There is a potential from there. Is that correct? It is called sheath potential. What kind of voltages so far I have applied? DC. Is that clear? I have applied DC voltage.

Typically kitna voltage lagan chahiye yadi feel eV tak le jana hai to? Toh 100 to 300 volts. At what pressure? Because that will be decided by pressure. Why it is decided by pressure? Large, no not just, mean free path is one additional feature. Something else it gives. If the pressure is low what does it mean? Number of gas molecules are less. Okay. So to clear the current density, you acquire larger than, is that clear to you? So you have to understand this that pressure also decides what are the voltages. So to create this kind of a I could have directly show you sputtering from here. This is what they use okay.

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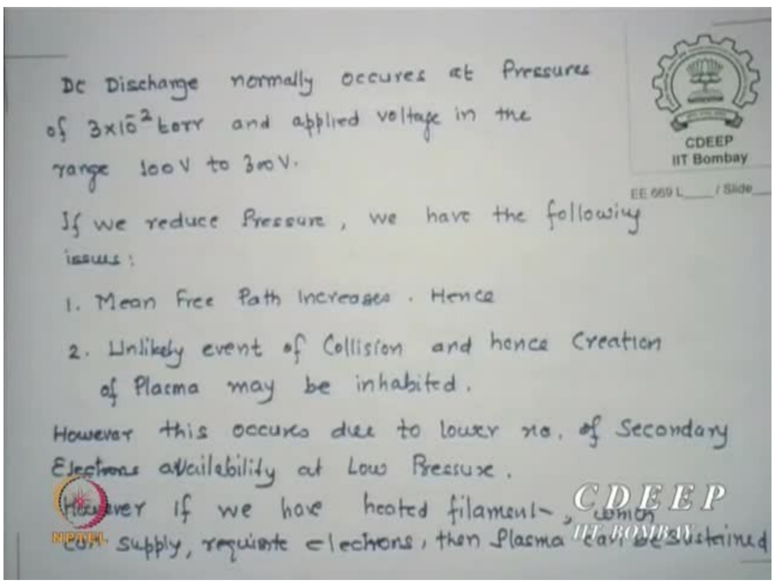

So if normally the DC discharge normally occurs at pressures around 3 into 10 to the power - 2 torr a typical allowed voltages of 100 to 300. If you reduce pressure, 2 things may happen. As you said, mean free path will increase but larger the mean free path means what? Lesser collisions. So even less plasma. So do not think that reducing pressure is all good. It has advantage in the sense, its purity. (())(46:31) but I do not want. So what I will do? I should do therefore what as you said is 1st actually vacuum as much as possible and then back fill it with gas.

So if you reduce the pressure, we may have 2 issues. Means free path increases and unlikely event of collision enhance creation of plasma maybe inhibited. Okay. So too small a pressure, or too larger a vacuum is not advised, though at times, in other systems evaporation it said reduced reduced, will not reduce here because essentially, it will not get sufficient secondary electrons, so no plasma. But that can be, we are short of electrons na? So if I provide you another source of electrons, all that you are looking for additional electrons to come.

Then I said okay, if that is your worry, I will apply you a filament heated electrode which I will call Cathode and it will emit electrons. Your short of electrons can be probably taken care and then what can I do? I can further reduce the pressure. So if I want to do lower pressure plasmas then I need additional electrons source which is from the filaments. Here is that figure. Everytime what I read throughout here is available mostly in the books as well, written in my own language.

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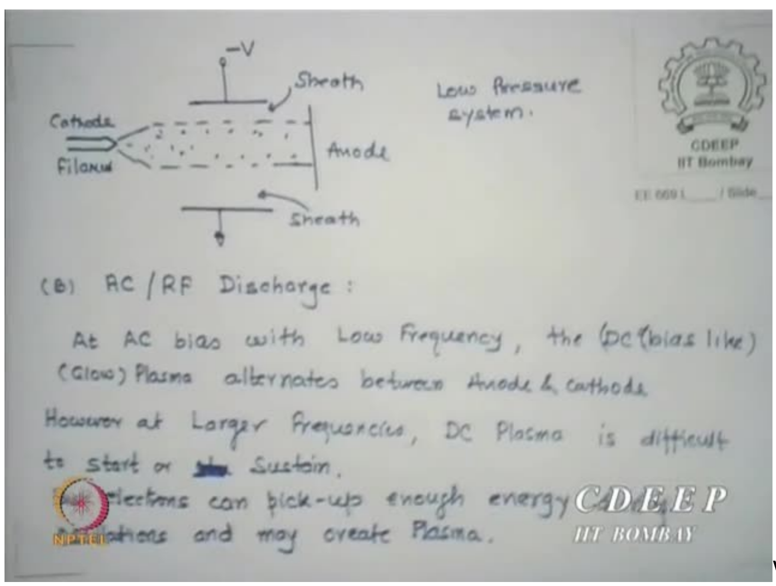

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So here is what a typical system will look like. I may have this anode cathode here, additional anode cathode here. I may apply a - potential here and I may have anode here and I may have a filament which may give me electrons. Sir, heat kiya, electrons mile, plasma tayyar ho gaya, upar ek aur plate laga diya maine. Wahan kya create ho jayega? Cathode fall jayega upar wahan bhi ek sheath (())(48:34). This is called plasma confinement. Kya kiya maine? Plasma ko confine kar diya. And now vacuum can be even mili (())(48:46), 10 to the power - 3, 2 into 10 to the power -

4, 8 into 10 to the power - 4, it can go even better vacuums for better this. Additionally you have to do a few things.

Now all along all this time, I was talking to you that there is a DC voltage I am applying. Is not it? DC voltage. So all the plasmas are what so far we discussed are called DC plasmas. We have done DC DC to apply and whatever charge discharge gas happened, we say it is a DC plasma. But in all our required systems, we do not use DC plasma. Actually, there is a DC diode sputtering but that is rarely in fact possible. But normally we will use RF sputtering or RF etching. So how does plasma is available to you in RF?

The reason why it is yes or no is this (())(49:46). If you applied DC is fine but if you apply very low frequency AC bias instead of DC, so what does the low frequency means? For a while, cathode will become anode, anode will become cathode but very slowly. Your frequency is very low. So the plasma during the time when it was one end, will only go from here to here from because it will create sheath here, then it will create sheath here. But it will keep oscillating. But essentially, equivalent to saying you have a DC discharge.

Though this keeps moving, but it has still a equivalent of DC discharge. However, if you increase the frequency, it cannot follow this movement. Whole bunch of plasma cannot go so fast. So there may not be plasma at all because if the voltage keeps changing, there is no time for ions to interact with, electrons will keep moving other side. So there may not be any ionisation at all if I apply an RF voltage but as I said, we want to use RF discharge. Ions may not follow the fields, RF fields but electrons can na? The advantage we take.

Electrons follow this fields, RF fields and pick up energies as slowly start and I think the gas. Because once they will go here, come back and hit again, again create ionized, they move up this side, will move there by that time, cycle asks you to come back. So electrons will keep moving and may finally because of acquiring the because the distance is small,, sufficient energy they can acquire in every transition and it will keep ionising the gas. This is called RF discharge. This is called RF discharge.

Now it is is very interesting, few data should be known to you. RF discharge has something also to do with pressures. Why pressure? Do you believe at lower pressure, high frequencies are sustainable or vice versa? I am asking you a question. If I reduced pressure, should I have to go on a lower frequency or higher frequency? Okay, do not think too much.

Student1. Higher frequency.

Student1. Higher.

Student1. Higher.

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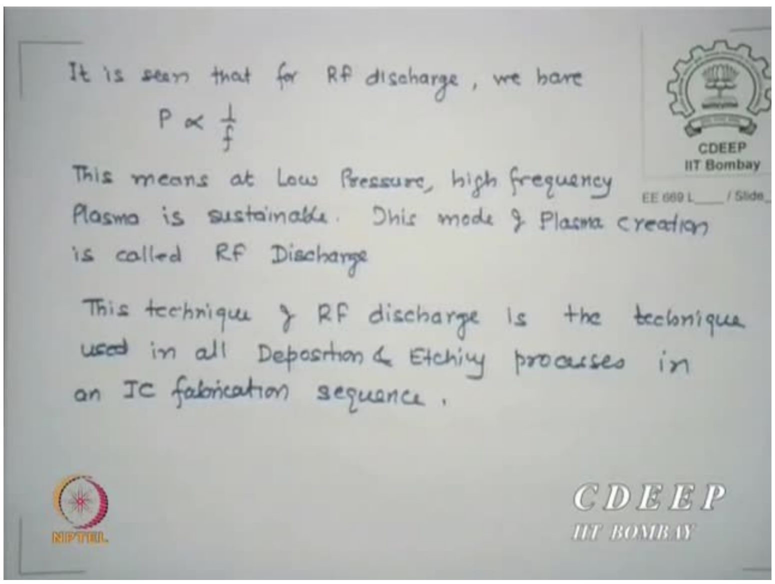

It is seen that RF discharge can occur at a pressure which is inversely proportional to sustaining frequencies okay, 1 upon F. If you have a lower pressure, you must work out higher frequencies. This mode of plasma creation is called RF plasma or RF discharge. This technique of RF discharge is the technique used in all deposition and etching processes in IC fabrication. But there they do not have to because electrons will ionise them. I do not want ions to move anyway na. I will not plasma to be sustained but what would have happened if they would have moved, then I will have to change the polarity comeback.

I do not want them to move anyway. These electrons will go and come back and they will keep gaining energy because they will pick up energy from the field and will heat the ions. After a while, they will ionise. Ion, then you have a (())(53:31). So it is called RF path. That is it. In DC, that would happen. Ions move but in RF it does not. So is that clear? So what is the all this crux? Itna sab DC padhane ke baad kahen, nahi nahi wo actually DC use nahi karenge. Fir kaayko padhaya? Because to know how RF works, I said how DC works. Is that okay?

You are the, I mean that is what I kept saying. Not that these are not known to many but I only want to impinge on you, these are relevant basics okay. Whether you like or do not like, but I believe you should know. Where is the people (())(54:14) looking for plasma?

Professor1. I did not get you.

Student1. Rocket propulsion.

Professor1. Yes, rocket propulsion is one. 3^{rd}, another one? We are trying to generate electricity, MHED project, fail ho raha hai abhi tak but someday. We need to start plasma at 6000 degrees centigrade. Now 1^{st} Sun temperature lao aur fir energy kahan se. Energy le hi aaye hum to. And then the efficiency is 30 percent. So 6000 degrees creation ki energy, 30 percent aapko return akrega. So energy ka hydrodynamics barabar nahi hai. Ye Kar lo, plasma hydrodynamics, you have a lot of game to play. You may become trillionaire if you succeed.

Of course the imagery system, is right now we are in government of all 5-6 big governments have spent $ 10 trillion and not succeeded okay. So they are powering now an hydrogen bomb inside so that the 6000 is reached okay. Now the safety of that if you fire a hydrogen bomb, you have a sun temperature you will reach. Then everything will remain or that also will go? So there are tricks for something.

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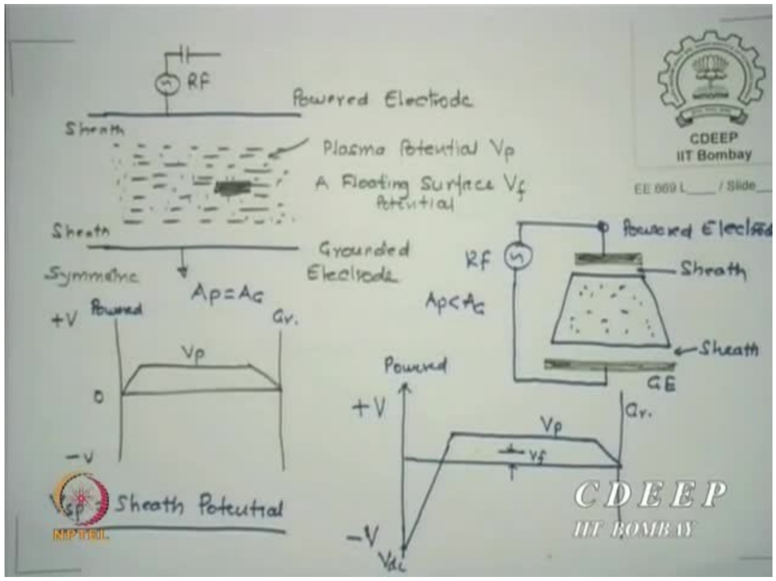

I belong to DAE. I was in Tata Institute of Fundamental Research. So I know much about atomic energies. Okay. Here is some RF system slide. There is a, in this case, we do not call anode or cathode. We say powered electrode where RF source is applied, the other is grounded electrode. And it so happens that you have sheath on both sides and we define a potential VP in the plasma add anything, any point in between, we say floating surface potential VF. We will discuss this later. This is an RF system. We are not showing you.

Here also, there will be a filament source to maintain electrons some once a while. Okay, so that I have not shown. I am right now only showing plasma system part. If I plot power vs distance, whatever the sheath potential, must be same as plasma potential. Jo drop hai wo total drop toh 0 hi hai. RH hai wo. Toh jitna potential P pe hai, utna hi sheath par hai. The difference here is, please take it, the way these 2 figures are, these areas we call powered electrode area and also we have ground electrode area, AP and AG. The 1st case we looked into is AP equal to AG.

So uniform sheath size is with reference to plasma. So we say, the sheath potential is same as plasma potential ,VP. However, in many a times, I may do this. What is that I have done here? The plasma powered area or rather power anode or this has smaller area than the ground ones, shown as an example. Or to say AP is smaller than AG and then if I plot the pile, I will maybe next time I will show you more. There will be a negative VDC across at the close end of the power, there will be a voltage drop VDC. Then the plsma potential and finally it goes to 0 at the ground.

Please remember, this DC potential here average DC potential is -. We will come, we will use this and therefore I am not detailing it but just take it. So this is called asymmetric electrodes. So many of the RF systems have asymmetric electrodes. This is asymmetric, this is asymmetric. We will come back to this part last if you draw figure, I will just show the equivalent circuit for this and we will stop for the day. What is the plasma essentially equivalently you can see? If we look at this figure or this figure, they but that is 1 upon omega C, depends on frequency, capacity. There is a resistance associated in the sheath. There is a resistance associated in the plasma. There is a resistance associated in the lower sheath.

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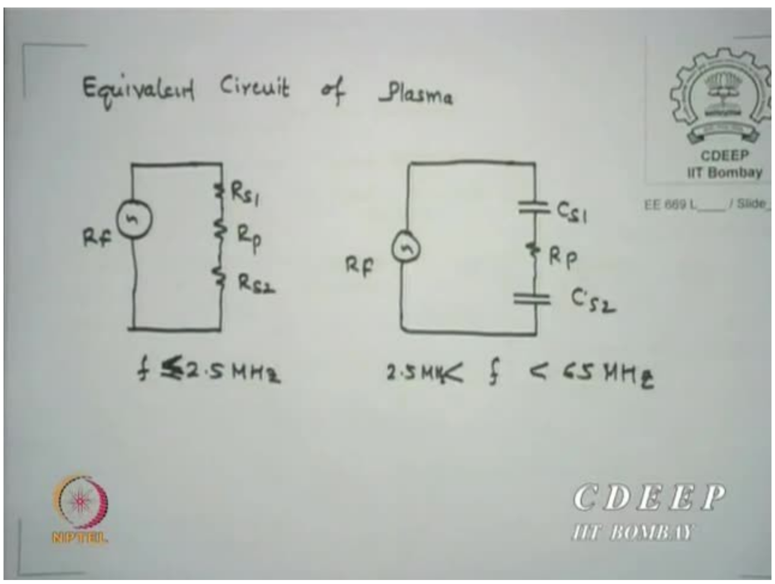

So if I look at it, here is the figure. When the frequencies are smaller, around 2 megahertz or over, the equivalent circuit of a plasma is RS1, the top sheath, plasma resistance and the lower sheath sheath resistance. And now someone wanted it just if you have too large actually, R parallel C hai. So whatever frequency is important, will decide which one to stick. If the frequencies are larger than 2.5 megahertz but smaller than 65 megahertz, this behaves more like a capacitance, sheath acts like a capacitance in between, plasma is why it is always resistance? Ions, electrons, conducting hai wo.

So at much higher frequency, it acts like a RC circuit and at lower frequencies, it acts like a resistive circuit. This is equivalent of a plasma. Before we quit, I may just tell you, all other frequency ranges or all RF systems, one can always say 65 megahertz or I can have kilo hertz or whatever frequencies but there are limitations of using some frequencies. Okay. These are called firstly there is a wireless standards which will not allow use to wireless bands. Then there is a problem with the industrial band which will not allow certain frequencies to be used by other people.

So there is some open band left. So typically all RF all RF or any frequency systems, hardly two frequencies we use. 454.5 kilo hertz, 454.5 kilo hertz is one frequency given to us, the other is 13.5 megahertz. The other is 13.5 megahertz. These are the 2 frequencies allowed for any integrated circuit manufacturers. Is that clear? So all system will either work at 454 kilo hertz in which case this is the equivalent. If it is 13.56 megahertz, this is the equivalent. 30 hmm? Upto 65 megahertz this circuit is valid. Beyond that, socho kya hoga? Surface properties will take care. So plasma nahi rahega. So is that okay? So only 2 frequencies, 454.5 and 13.5 megahertz these are the 2 bands given, 2 frequencies given to us or any of the integrate circuit manufacturer has to use all over the world. All over the world, it is not us, it is all over the world okay. So you buy only these 2 frequency sources, it will be (())(62:12). So with this gives you some idea of plasma. Now next time, we will use this to create sputtering system, repulsion system, etching system. Same thing. Just play games, it will do one or the other, okay. See you then.