Technology of Surface Coating
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Lecture No 17
Radio Frequency and Pulsed DC Sputtering

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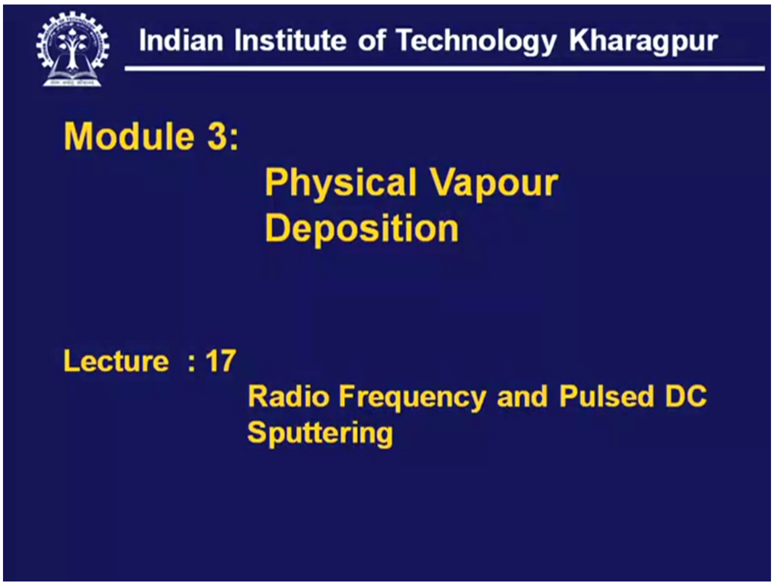

Radio frequency and pulsed DC sputtering, this topic we are going to discuss today. Now why do we need this radio-frequency sputtering or pulsed DC that means in this case the power supply will be available at a sinusoidal form that means this voltage which will be supplied to the electron that will keep on changing with the time and this frequency will be very high order and why do we need it? Normally DC sputtering is well-known for well-established technology for depositing the material by sputtering. However, the problem appears when it is a one electrically nonconductive material, so we can compare that DC supply and one alternating supply against one electrode which is non-conducting in nature.

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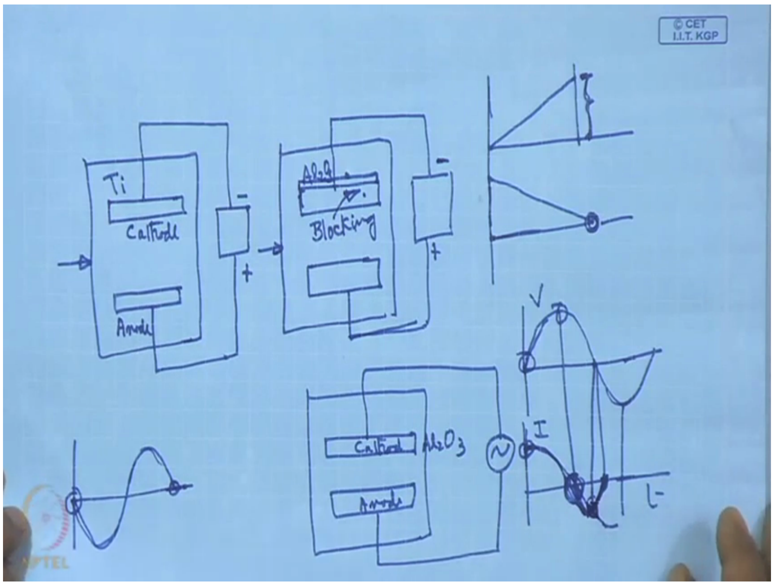

Now let us have a quick look this is one target which is actually provide with this negative polarity and here say we have the anode and this is the positive polarity which is within an vacuum chamber. Now this target so this is actually the anode and this is the cathode which is polarized with this negative biased and this is this can be a conductor. However, when we have a material which is non-conductors say for example in this case this is a non-conductor this target material and we can illustrate say this is titanium or aluminium and say this is aluminium oxide which is non-conductor now in this case we have all the relevant or the required features of sputtering.

However, one thing that is missing here that is the conductivity of this material. So as a result what is going to happen in this case that this will be polarized and then there will be accumulation of charge, there will be no conducting path at means though we have a cathode plate just behind it but on the top of this cathode plate we have one target material which is non-conductor, so there will be accumulation of charge and it will ultimately lead to heating of the target and it can even lead to arc discharge which is the most undesirable scene in this whole sputtering process, so here if we look at that it is just like, we can see very well that this is actually a capacity coupling along with the power supply and with this electrode.

So it is almost it can call it a blocking electrode, it is actually blocking this conduction, so this is actually blocking electrodes and in this case if we apply the voltage then what is going to happen? That in this case there will be increased in, so I mean gradually there will be increase in voltage but at the same time there will be actually fall of this charging current, so this will be actually the limit and here we have this charging current has come to 0 and after that there will be no further charging. So this is going to happen in this case when we apply a DC against one non-conducting electrodes and this is going to happen but if we apply one alternating supply about this, this is the non-conducting electrodes and against this we have one alternating supply and this is going to be the anode and this is the cathode and anode and this is non-conducting.

So in this case what we can see normally when it is, when a capacitor is coupled to a alternating supply, we can see just following this what is going to happen that if it is the sinusoidal voltage which is following a sign curve then we have a current like this and this is going to be maximum at this point, so this is going to be maximum at this point and it will follow this particular form. Now what is important here to know, so this is voltage and this is just the current with time and this is the form, so here it is maximum corresponding 0 current and here it is 0 voltage and we have was the maximum and here also we have this negative maximum, so this way we can follow this sign wave but what is important here to know that within one cycle, within one cycle the net current flow to this capacitively coupled device against this alternative voltage that is going to be 0 that means it is going to be 0 over this 1 full cycle, so in case of DC it is one directional and it is coming almost to 0 but in this case alternating it is following this sign curve. Now this is going to be the case when we have in a circuit just one capacitor and along with an alternating power supply.

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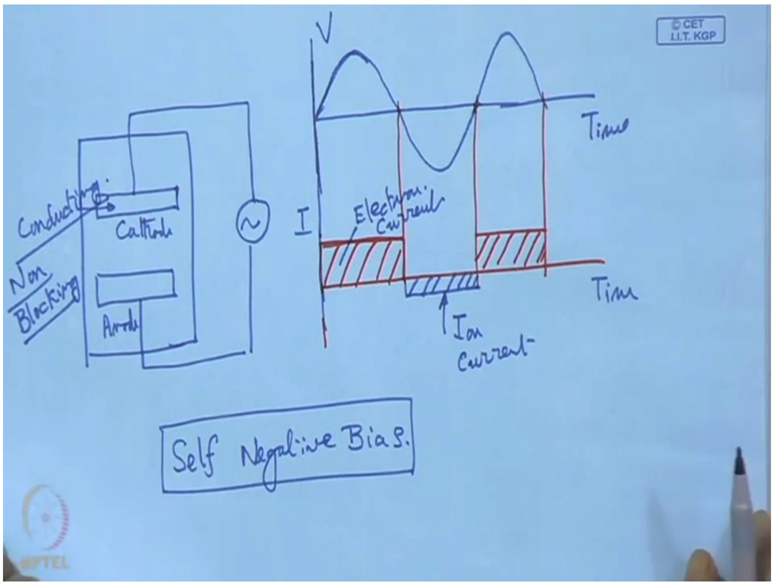

However, when we have this thing, when we have this here that means one conducting cathode or conducting target and which is actually supplied which is actually provided with this alternating voltage and this is within this chamber then what is going to happen? So this is cathode and this is anode then the form will be more or less like this, so this will be a form, this will be positive part of the cycle and this is the negative part of the cycle and here what would be interesting, so this is for the voltage that this electrode voltage and this is time and if we draw the current characteristics and we can have in this form, so this is the positive part, naturally here the electrode will draw electron current and this electron current is going to be plus in that, so it will be this amount if we put on an average.

This is going to be the electron current and for this half of the cycle this is going to be the ion current and in the next half it will be again the positive that means the electron current. So this will repeat itself but one thing we can see here this is current and this is time, so this is electron current and this is actually ion current. However, what we see here the magnitude of the electron current is higher than that of the ion current, it is not surprising considering higher mobility of the electron compared to that ion current, so the less mobility of ion current means less amount of less amount of ion current and higher mobility of electron means the same applied voltage we have larger magnitude of electron current but one thing is that if it is this will happen if it is a conducting cathode, conducting cathode that means we call it non-blocking cathode, non-blocking.

However, when we have a non-blocking cathode whether it is AC or DC most important thing here is to have a self-bias that means a self-negative bias on the cathode surface, so on this cathode surface a self-negative bias voltage must develop, why? This is necessary to pull the ions which will do the necessary dislodgement, injection of the sputtered material from this cathode surface and in addition secondary electron also from that cathode surface, so self-bias is anyway it is a must or this sustaining the discharge or to carry forward this sputtering process. So when it is a conducting cathode or non-blocking cathode, what is also added here in in in this system that is what we call a blocking capacitor.

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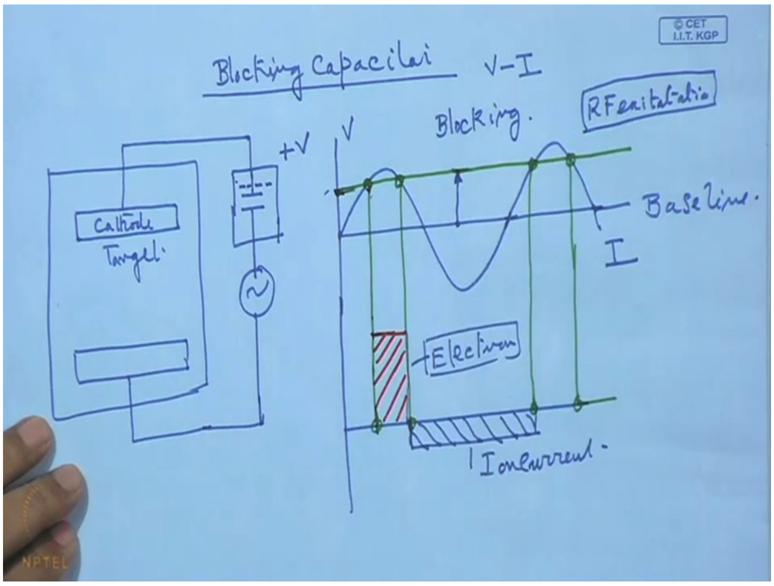

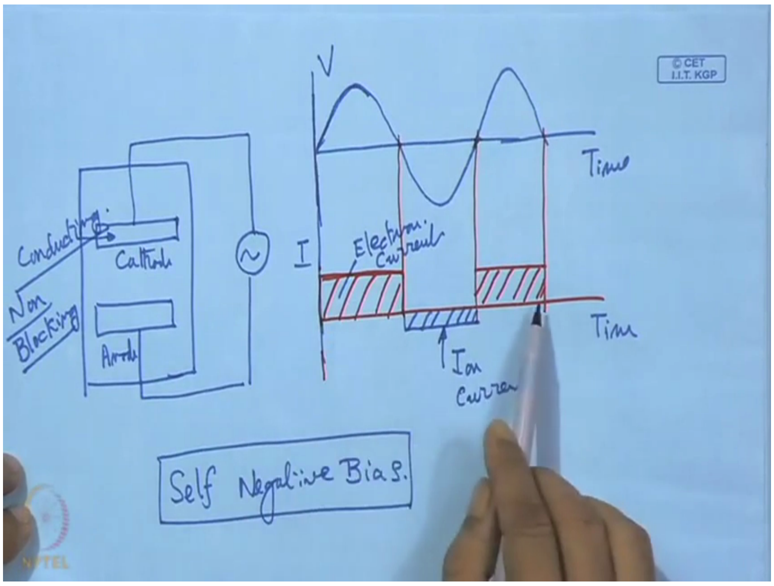

It is called a blocking capacitor, now with this blocking, so this diagram will be slightly modified that this is actually the cathode which is the target and just facing this will be the anode and here what we have, we have a blocking capacitor and this is the capacitor and then followed by we have this alternating supply. Whole thing will be encased in this vacuum chamber and in this case this is going to be this when it is plus V we have, we have your negative charge accumulation of negative charge. The reason is that that when we treat the positively polarized, it will draw huge amount of electron in comparison to the ion in the next half cycle and has a result this upper plate of this capacitor that will be negatively charged.

However, this blocking capacitor, capacitor it has the main rule to induce, to create an negative bias on this cathode surface and as a result of this what we must understand that in this case the net flow go through the circuit that will be in a full cycle that must be 0, so to accomplish that to fulfil that requirement one has to see that the net amount of electron flow and that of ion flow in each half of the cycle considering one full cycle they are net amount will be 0 that means ion current and total electron current that should neutralise each other and if that should be the case then what we can find here that this is actually the sinusoidal form of the voltage and just keeping this form here what we have to do, we have to now shift, so this is now the baseline, this is now the baseline or the 0 line.

This has to be shifted towards the surface that means this baseline will be shifted somewhere here, so that we can show by this green line, so if this is the shift that takes place here then what we find interestingly these are the points what one can identify and within that zone what we find here, so this is going to be a span over which this electron current will flow and this is the span of this length of time over which ion current will flow and this is also the span over which the electron current will flow, so in this case it should be such that if we can have may be this amount, this is the net flow of electron current and at the same time, so from this point to this point that will actually constitute one cycle and in the next part this is going to be the portion where ion current will flow such that this area under the curve which is shown by this red hash mark and which is shown by this blue hash mark.

Numerically they should be equal that means this is on the negative side which is ion current and this is also electron current and numerically this area and this area must be same and this is simply possible just by if we look here this was the original 0 line or baseline and this is possible just by shifting this blue line and positioning it here along this green line and its location will depend on that, that it will be positioned in such a manner that this area and this area they are saying, so from this we can see that with respect to this one, with respect to this one this whole curve is shifted towards this negative side and in that case we can see that there is a negative bias on this cathode surface to which this surface which is subjected to this alternating voltage but on that superimposed and negative DC this negative bias and that will now assist in getting this ion towards the surface and it can do the necessary sputtering from this target and this is possible just by use of this blocking capacitor.

So here we call it a blocking electron. It is the actually this diagram we should say, so this is I, this is V, so this is the V I characteristics, so this diagram we should call it a V I characteristics of a blocking electrode when it is submitted or subjected to RF excitation, so when it is excitation, when it is submitted to this RF excitation then a blocking electrodes should behave following this V I characteristics and when it is a non-blocking we can see that there is a flow of current through this circuit and in this case this electron current and ion current they are not numerically equal.

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So the whole question is that this use of AC power source at radio-frequency and this radio-frequency it is a very high frequency, so is a well standardised value everybody use this megahertz and that is the frequency which is reserved for all this sputtering devices and that is will consider and well accepted at the International by the International community to follow this standard.

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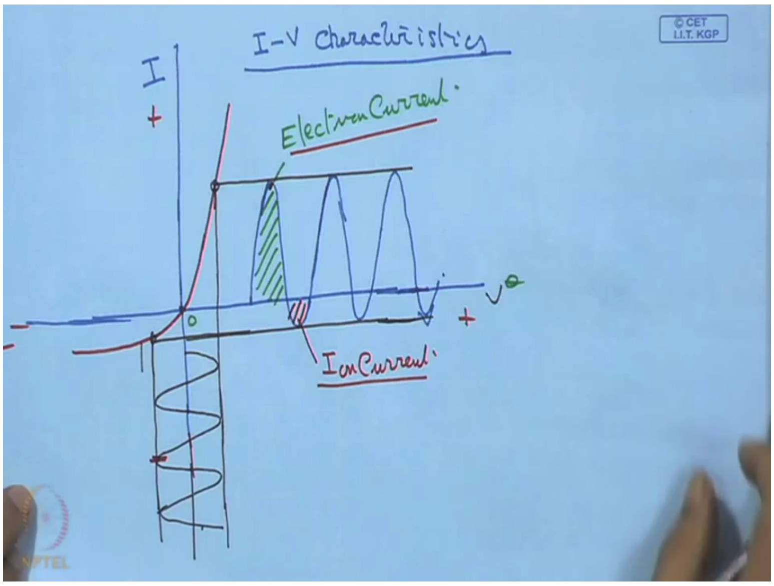

Now this development of negative self-bias voltage on a non-conducting target surface, this we have been discussing and how it has developed but this can be also explained in another way and let us have a quick look here that if we draw another diagram showing this V I characteristics this is actually I and this is V, so it is also I - V characteristics, I - V characteristics of the one electron which is immersed in a plasma volume, okay. Now here it is a typical curve, so this curve nature is almost like there is let us try to draw. It is somewhere like there, okay. What is the significance of this? What we see, so this is actually positive current, positive means we accepted as electron current and this is this and this is minus this is also plus this is minus, so this is negative polarity ion current, positive polarity electron current.

Now on that, so that is the I - V characteristics of the electron which is immersed in a plasma volume. Now what we do here over this we have to superimpose one AC, so one AC has to be superimposed over this, so it will be symmetrical over this 0 line, so let us have a quick look here, so this is something what we can find, so this is the super imposition and it will be a sinusoidal curve it will go like this. Now so this is actually the 2 extremities, so if we extend these 2 lines what we get here? What is the significance of these 2 borders? Now these 2 borders are nothing but the 2 peak value one is the positive peak another is the negative peak, so here what we find this is the input, this is the input and we get this cathode current as the output and it will follow this curve, it will follow this, okay.

So finally what we find here that this part of this cycle which is about this 0 line, this is, this is the baseline, so this is actually the electron current and which is below the baseline, which is below the baseline that we call ion current, okay. So what we see that this plate or the electron which is non-conductor and which is capacitively coupled in this plasma volume there we have such kind of characteristics but it contradicts the basic principle of a capacitance which is placed inside this plasma volume and which is subjected to 1 alternating supply, so when it is a capacitively coupled then the net current through this capacitor over one cycle that must be 0. In another word what can be said that when it is 1 alternating supply, there cannot be any DC direct flow of current over the cycle that means simply that this area under this curve or this peak from this baseline which is quite different. Here we have excess electron current that should not happen physically in practice, so we have to redraw this diagram, readjust this diagram and then let us see how this equalisation is possible.

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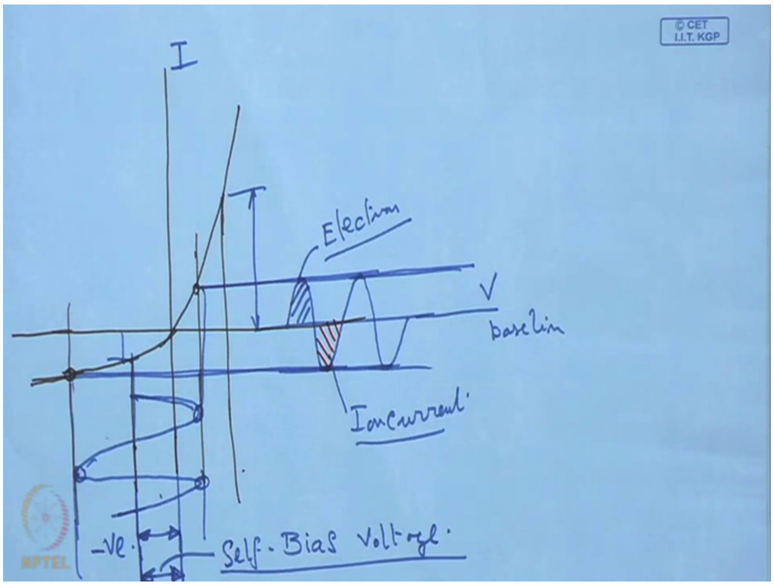

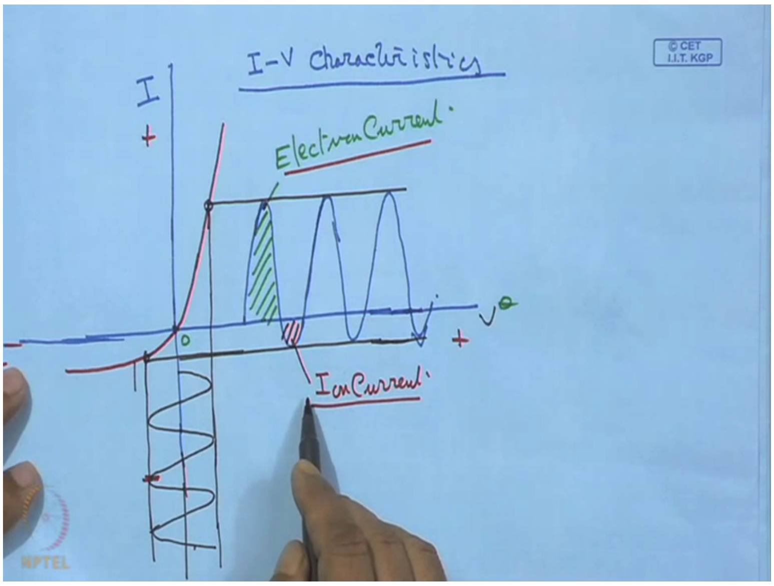

So we have to have little adjustment over these and this is the characteristic curve and what we have drawn here, so what we can see from this point that this width and this width they are not same, so we have to find out a position maybe we can find it like this, we have to find out a position say this is a position and this is a position and these are some border or the bandwidth over which if we draw these 2 lines, if we draw these 2 lines then what we see that now this wave form, it has taken a different shape and also different magnitude and what is most interesting thing to see here that about this baseline this net flow of electron current and that of the ion current those are equal in magnitude and this has been made possible just by shifting this baseline from this y-axis that means if we consider the previous diagram here the sinusoidal, this external input variable that was applied about this y-axis and as a result we had excess electron current and small magnitude of ion current but if we shift this baseline, what we have tried to do this baseline is shifted from this point to this point.

So that now we have this input that means now this is going to be the input between these 2 points, so these are the 2 boundaries, so this is now the input. So this point is transferred here and this point is transferred here, so this is the input signal, this is actually the applied cathode voltage and this is the cathode current and just by shifting this baseline from this line, we can get equalisation of electron current and ion current and that is exactly the condition one has to fulfil when this electrodes is a non-conducting electron or a blocking electron or which is serving just like a capacitor and in that case what we see that this is actually the self-biased, this is actually the self-biased.

Self-biased means the voltage which is which develops on the cathode surface and this is obviously negative in nature, so from this illustration also we understand that a self-biased is developed on the cathode surface of a it is non-conducting cathode or target surface and this is possible because of this alternating supply and other same time this electrodes is serving just like a capacitor it in that circuit. Now this blocking capacitor it has one rule, if it is a conducting material, so we see how it is developed.

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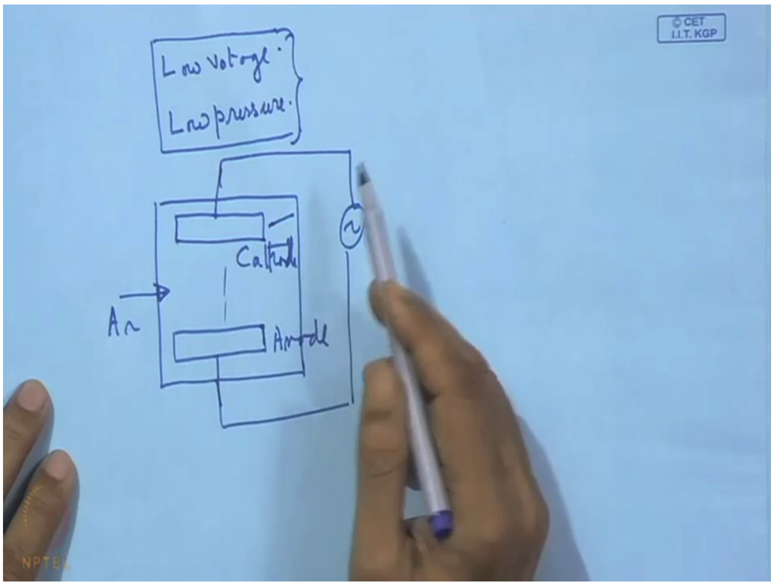

Now advantage of RF sputtering there are many, so one of this advantage is that here what we see number 1 requirement of low voltage, requirement of low-pressure. These are the 2 greatest achievements with this RF and also what is that very important that for non-conducting material and this is one of the most suitable processes to initiate this sputtering or to conduct this sputtering process. However, for conducting material also it is possible but in that case we need a blocking capacitor as a peripheral support and also a matching network these are 2 important things with the sputtering device.

Now low voltage and low pressure these are the 2 important things one can identify extremely advantageous to carry out or to conduct this sputtering process. The whole idea here is that the if we consider one cathode and one anode, one can recognize the very advantage of this alternating supply, we have argon and then it is 1 alternating supply, so this is cathode and one anode plate or the valve may be also anode but what is important here one can see that the whole thing, this secondary electrons instead of so that will emerge out from the cathode, had it been DC and then that will be pulled in this plasma volume where they become primary electron and with collision or even without any collision they can strike the anode surface and they can get lost.

That means we can immediately understand that this secondary electron which become primary electron in this plasma volume, they are not properly utilised if they have just a directional flow and finally they are going to strike the anode it can be one anode plate or it can be the valve of the chamber which can also serve as anode. However, when it is 1 alternating supply, alternating field in that case this electrons will keep on oscillating, it will be swinging motion back and forth between these 2 because in one cycle, in half cycle this voltage will change its polarity, so when it is going to be a negative one that will be brought on this side and when this anode because this is it is just not anode, we should call it electrode.

These are the 2 electrodes so they are changing their character from positive to negative, so this is the electrode which is actually the target and this is the other secondary electron and within that in between in this inter-electrode space that will keep on oscillating and swinging and through that there are more chances of heating just not one argon neutral but many more before they are really exhausted and lose the energy. So one can immediately understand the efficiency or utilisation is augmented and improved a lot just by providing this oscillating motion to this electron and that is possible just by giving this alternating voltage over there is across this 2 electrodes which are put inside this sputtering chamber. So that is actually the main reason why with low voltage and low-pressure it is possible to handle this sputtering with greater efficiency and naturally or one who is interested in sputtering this is one of the very important issue one can consider. So this is actually a summary of RF sputtering.

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But here use of RF power source for conducting target this is already understood that for conducting target an auto development or self-biasing just is not possible because it is a conducting current and that has been already illustrated. So you are what is important have a blocking capacitor and along with that we have a matching network and this matching network ensures that there is power transfer from the power source to the plasma in the most efficient way and that is the optimum power supply that means there is actually a resonant circuit comprising a inductance, a capacitance and there should be a resonance.

So that the circuit can draw large amount of current from the power source which can be transmitted to the plasma, so that is why this is called in technical terms we matching box, so it is actually a blocking capacitor and this matchbox for fine tuning of this power supply with this resonant circuit in in tune with the plasma so that best possible way of power transfer is possible. However, these are the high order technical complexity but this is actually are complicated hardware of the sputtering system one can also realize.

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So this is actually complexity of the RF power source and if we consider this as not so simple to realize and this is also the ground reality that scaling up or commercialisation of the process to suit a particular application that also becomes its limitation. So industrialisation of this sputtering technology for mass scale production of the coated product and also the development and design of this matching network and the tuning circuit those other 2 complicated task in the realisation of sputtering system though it allows one to conduct this sputtering with low voltage and low pressure and that is one of the greatest advantage of this RF sputtering even for a conducting material.

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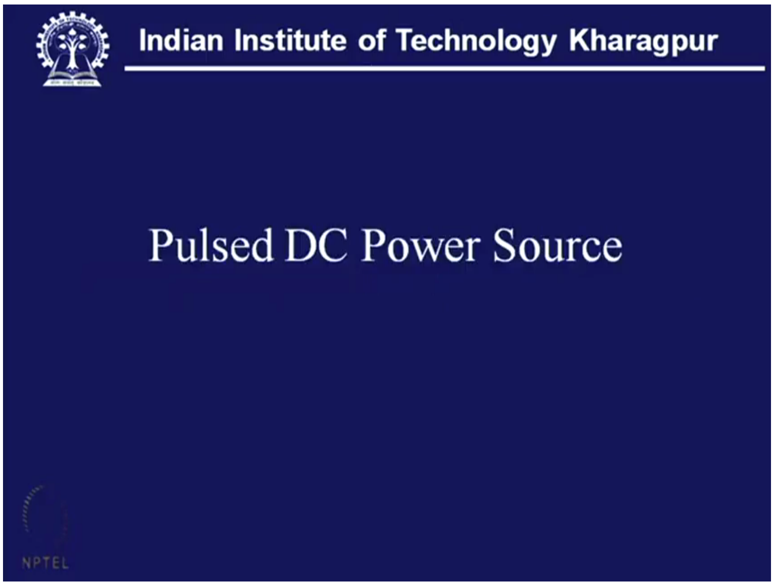

So what are those materials of immediate interest will be say for example non-conducting material having poor conductivity say in material ceramic group it can be some oxide of metal, it can be some sulphide of metal though nitride, carbides are usually conducting but say tungsten disulphide, molybdenum disulphide which are of immediate interest in tribological application or ceramic coating which is also has an interesting application in heat shielding and also in wire resistance for those this RF sputtering would be one of the process of immediate interest. Now having realised the complexity of this RF technology people actually made a thorough search on an alternative to this sputtering and as a result of that this pulse DC power source that came into being, so what is that pulse DC power source.

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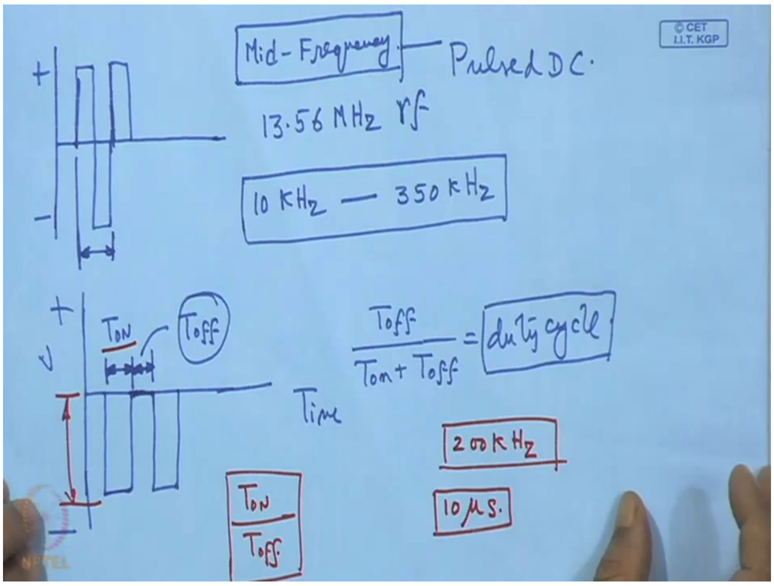

In this case it is actually a DC and this DC it is a DC with some chopping and interruption, so it can have both it can swing between us and minus and it can be different form of pulse it can be square or rectangle and normally this can be like this, so it is a positive polarisation, negative polarisation, so this is actually once 1 pulse width, now this is pulse DC power source that is actually called mid frequency, mid-frequency. Mid-frequency, pulse DC it is not that high-frequency as we normally referred to 13.56 megahertz in case of RF but this mid frequency that is good for this pulse DC and that is maybe from 10 kilohertz to say now as of now 350 kilohertz that power supply is available commercially and for use.

So this is a zone which we call mid frequency, so 10 kilohertz to 350 kilohertz and here one can change this width that means the pulse width and also the magnitude of the pulse, so there are lots of variations possible with such an option with the power supply and this can be one of the area of interest for those interested in sputtering technology and this is going to be and being used as one of the alternative to this RF sputtering.

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Now in this mid frequency pulse DC, what we can do? We have lots of options single magnetron unipolar pulsing, now single magnetron unipolar pulsing means this can be a form and this is 0 and it can go like that the reason is as follows, this is timescale, this is voltage plus minus because anyway we have to polarized this target surface with negative voltage, negative voltage and that is why we put this minus on this side and here what we see further to this that this is minus and this is set to 0 that means it is negatively biased and in one part of the full cycle is also put to 0, so this is actually called this is called T on and this part that we called T off, okay and this T off and by T on that means the total this pulse width that call actually duty cycle.

This is one important term in in that it is actually representing the activity. Actually what is going to happen one must understand here that when we negatively polarized, there is accumulation of charge whether it is RA for pulse DC but since we would not allow this to happen or a very long period and that one can see by this T on, so when it is actually say 200 kilohertz and 200 kilohertz means pulse width is actually 10 microsecond, so this is going to be 10 microsecond and out of this 10 microsecond 1 has to decide upon how much will be T on and what the remaining will be T off.

Now what will be T on T off that would be quite interesting in that, we can allow this thing to get charged that means it will be negatively polarized the cathode that extend which will be set and which will not lead to very damaging arc discharge, so that is the limit we should not allow this thing to happen this arc discharge and undesirable and unnecessary heating of the target, so before that we must chop it and this chopping is done here, so maybe here we can have 20 percent duty cycle or 40 percent duty cycle this also depends upon this impressed voltage, so based on that experience one can decide upon what should be the duty cycle but at the same time one should look into this point and should not ignore that is the productivity.

One thing in the whole process to protect the target and or not to arrive at or not to arrive at a situation very damaging that means arc discharge that should be avoided anyway but at the same time the productivity one can see that had it been 100 percent that would have been the best but we cannot do that, so we must have T off and that should be as minimal as possible just adequate to avoid arc discharge. Now this we can have other variations too. So this is actually what we call it is a single magnetron which means we have a single cathode and on that this can be applied.

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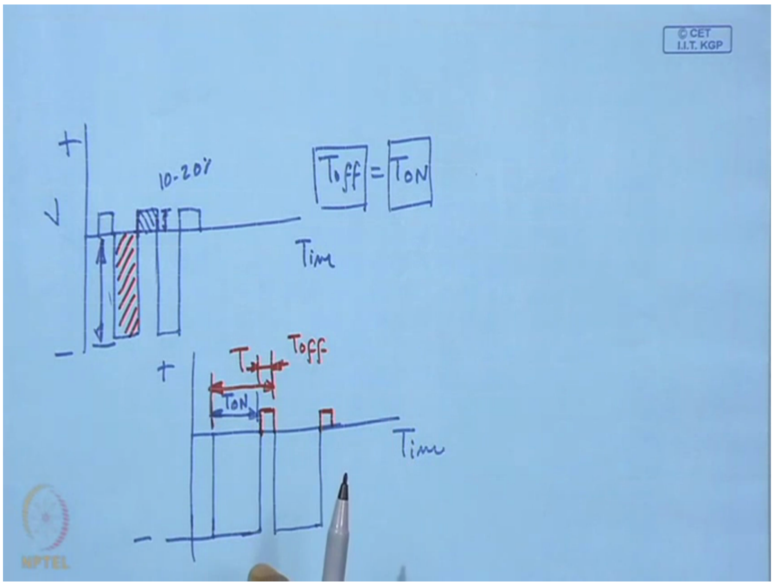

So following that we have another one single magnetron but it is bipolar pulsing, single magnetron bipolar pulsing, so here what we do this is also single magnetron but here we have little bit of positive polarisation and the process repeats itself it is something like this, so this is actually the active part of the whole cycle that means the target cathode is negatively polarized and this side it is actually positively polarized and this positive polarisation means there will be accumulation of charge and that has to be neutralised and to ensure that the whole thing is neutralised here.

So we have to have little bit of positive biasing to ensure that all accumulated charge during this period that is totally discharged and it is at the 0 level and the process of activation of the cathode can again start, so this is actually single magnetron with bipolar pulsing but here this positive polarisation that magnitude maybe it is around 10 to 20 percent...this is time and this is voltage plus minus. This part may be just this magnitude maybe just 10 to 20 percent of that what we put here and that is good enough to ensure than the total charge is totally neutralised by this positive polarity.

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Now here what we have seen the 1st 2 cases this is symmetric, it is symmetrical means that means on and off that means here T off is equal to T on, so off time is equal to on time and with that if that we have one possibility but it can be so that…single magnetron asymmetric bipolar pulsing and this is going to be in this form that this is the negative polarity that means here the cathode is active and this is the active part of the cycle with this negative polarity this is positive, this is negative, this is the time axis and then what we have little bit of positive polarisation but for a short period very short period and then it will repeat and it will follow what has been explain by this blue line.

So this is also one possibility but here one have to be extremely careful that though this is the total duty total time T and out of this, this is just T off that means this is the duty cycle and this is T on, T on. So this is also one way of getting anything done and in most of the cases this is also one consideration to have little bit of positive polarisation and this of period is a small percentage of the total time width or pulse width, so this is not symmetric, so neither in terms of polarisation nor in terms of a (())(52:25) of the on and off time.

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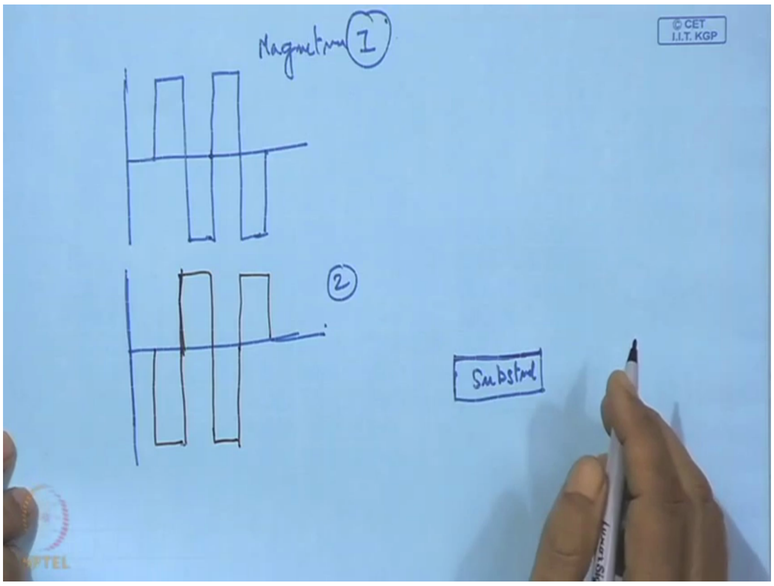

Now we have here dual magnetron symmetrical bipolar pulsing, now this one we can also look here we can have this illustration we have 2 magnetron and one may be following this cycle, this pattern, so this is for say magnetron 1 or the cathode 1, magnetron 1 and this is going to be the magnetron 2. What is the advantage in this case? So this is 2, so what we see that one pulse generator you must have the pulse generator and this pulse generator has to be coupled but in this case just one also generator can be coupled with 2 targets which are like twin target and when one is on the positive under positive polarisation, the other one will be with negative polarisation and this way one power supply can be well utilised.

So one is active and other is at that point is not active but their accumulated charges are neutralised and 2 are functional and this they can be made functional just by use of one pulse generator. In fact in all these machines we have we can have the pulse generator for 2 targets or we can have 4 targets. Even the substrate and be also having this pulse generator supply because of the simple reason that the cathode, the substrate surface may be a conductor but once a non-conducting film is deposited on the surface then the DC supply will not work for a conducting material substrate a DC would be sufficient but when it has a they has a deposited film of non-conducting material then one need this RF or pulse this DC pulse supply, so this is true for also RF sputtering, so once this non-conducting material arrives and cover this whole surface then it becomes almost like a non-conducting substrate and proper arrangement has to be made so that we can have such kind of biasing.

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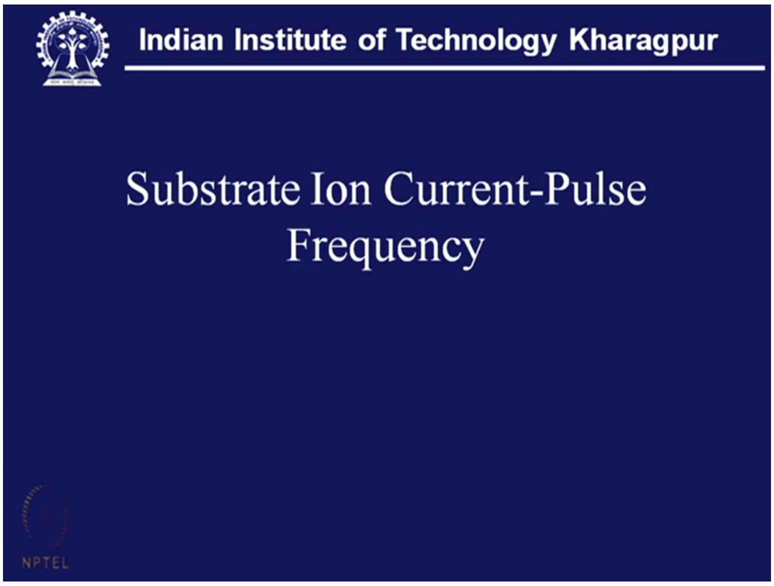

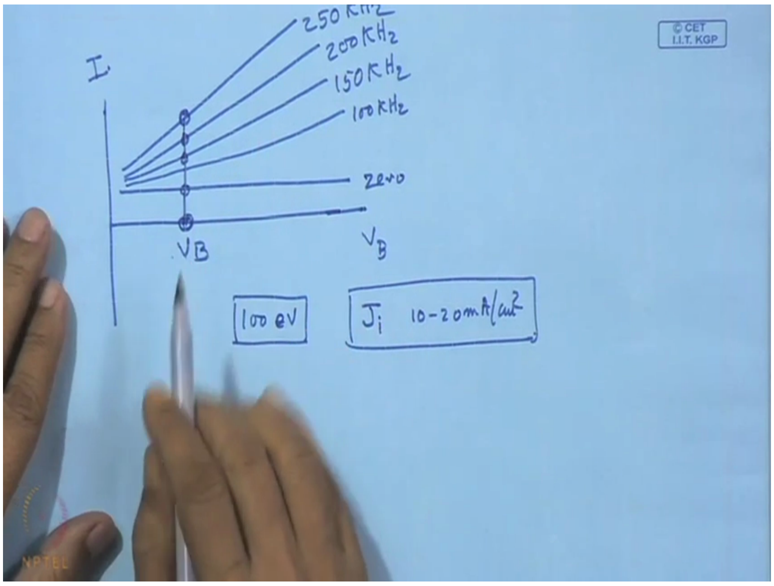

So substrate ion current pulse frequency, so this is one very important graph in that normally what we see substrate ion current I and substrate voltage. Now what we see normally it becomes say saturated, so with increased of voltage hardly we can increase the current but what we have seen that when we increase the frequency, when we increase the frequency we can have such kind of graph and this can be say this is with 0 frequency and this one 100 kilohertz, 150 kilohertz, 200 kilohertz or 250 kilohertz that means what we can see for one biased voltage here just for this VB maybe it is 100 volt or somewhere around just with 0 this is the value which does not increase but what we can see now since it is under pulsation.

So with voltage it will also increase but again at the same low voltage if we keep on changing their frequency, we can also get this current substrate current at an enhanced rate and there is one way very advantages the whole idea here is that with a low biasing we must have proper enhancement of ion current that means with low iron energy which is less than minus 100 electron volt, we should be able to draw current and such that the ion current density that may be in the order of 10 to 20 milliamp per square centimetre of the substrate, so this is very important parameter and that we can achieve with just by enhancement of this pulse frequency and with this DC supply.

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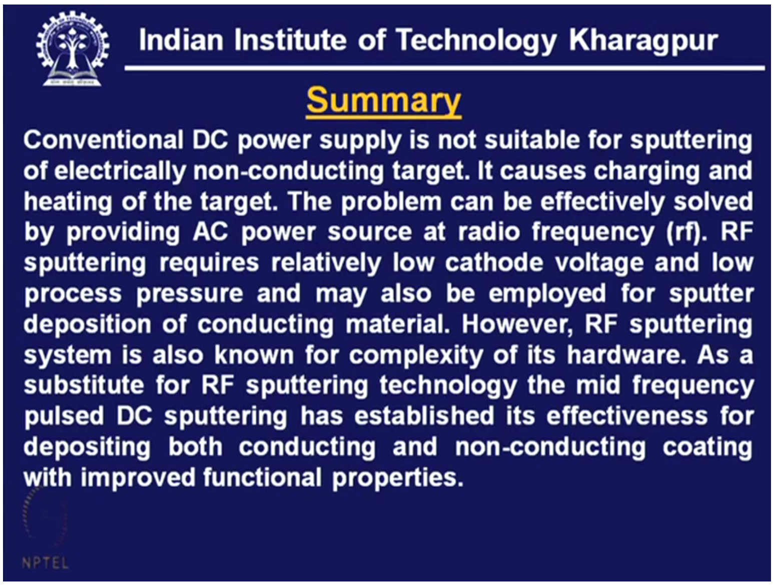

So with that we come to the summary which can state and be stated as conventional DC power supply is not suitable for sputtering of electrically non-conducting target. It causes charging and heating of the target and finally lead to arc discharge stopped this problem can be effectively solved by providing easy powers so is at radio-frequency which is in the order of 13.56 megahertz. RF sputtering requires relatively low cathode voltage and low process pressure which is definitely advantageous and may also be employed for sputter deposition of conducting materials.

However, RF sputtering system is also known for its complexity particularly for tuning the circuit this matching along with the plasma, so that highest possible power supply should be possible and this design of the blocking capacitor. As a substitute for RF sputtering technology the mid-frequency pulsed DC sputtering has established its effectiveness for depositing both the conducting an non-conducting coating with improved functional properties.