Technology of Surface Coating
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Module 1
Lecture No 16
Unbalanced Magnetron Sputtering

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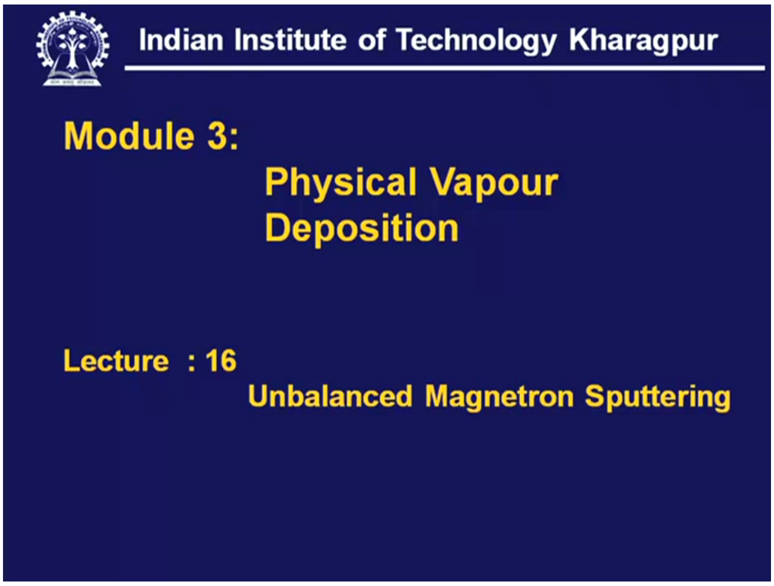

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Module 3:

Physical Vapour Deposition

Lecture : 16

Unbalanced Magnetron Sputtering

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Conventional Magnetron
or
Balanced Magnetron

Okay today we shall discuss the topic of unbalanced magnetron sputtering. Now we have already conventional magnetron or balanced magnetron and if we have a close look to this, we can just illustrate by this simple figure.

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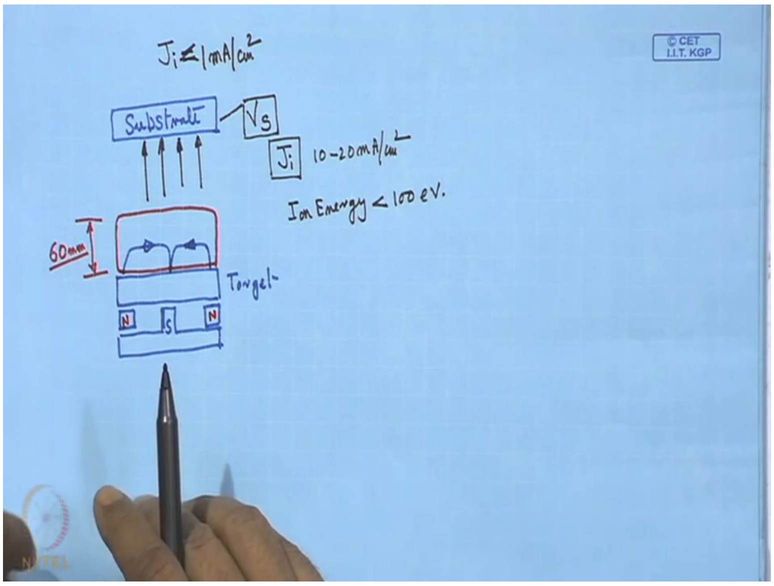

So this is actually the target or the cathode and behind this we have 2 magnets and this one… that means here we have 2 magnets and this is actually the ring magnet, the peripheral. This is the ring magnet and that is the central magnet which has this South Pole. Now here is lines of force are closed between this north and south, so we can draw this thing and this lines of force, this field that is parallel to the surface and this way the lines of force are closing themselves between North and South, so this North Pole and South Pole, they are of the same field strength and what we can have? Just if this is the target above this there should be one substrate that means this will be the receiver and this is the receptor surface where the reflux of coating, the sputtered material that will be intercepted and this will come in the form of condensed film.

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Conventional Magnetron
or
Balanced Magnetron

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Now here the existence of the plasma or this plasma volume is very important. Now what we can see here the plasma volume. Now this plasma volume is created over this and it is also known that this plasma volume more or less this region is 60 millimetre along around 60 millimetre wide, so if a substrate is placed within this plasma volume then it is also subjected to this iron impingement and the whole thing is full of secondary electron that means this secondary electrons that are confined within this volume, so if the substrate is placed within this, so this will be also submitted to this ion impingement and also the ion flux that will impinge on this surface with certain flux density and certain ion energy.

So in that case reasonably we can expect a dense film on the substrate when it is within this plasma volume goes width is around 60 millimetre, however if this substrate is placed outside this plasma volume then what we can see that in that case the ion current density that means the substrate ion current density that will be very less, so in that case we can write Ji which stand for this ion current density that will be actually that will be actually less than 1 milliampere per centimetre square and this will be the situation when these substrate is placed outside this plasma volume which is marked by this red line.

Now in that case there would be one very special situation that means the plasma outside that will be less dense and here it is a dense plasma and here it is a weak plasma field and as a result of that this plasma density which is low, that cannot cause production of a well dense film over the surface, so in that case this coating will lack all the mechanical property like hardness, cohesion and adhesion, however this lack of asthma density for this substrate which is outside this plasma volume for that there can be a compensation.

There can be a compensation means in this case perhaps one would try to increase the substrate bias V s, substrate bias so that we can also have high ion energy and this high ion energy is expected to have a strong impingement or strong bombardment on the surface, however this is not the best solution in principle what is necessary high ion flux density that means at Ji should be rather high maybe an indicative value may be between 10 to 20 milliampere per centimetre square.

This can be one of ideal ion current density or substrate current density that means ion flux is the density and other same time the iron energy that should not exceed a value of, it should not exceed say half 100 electron volt, so this should be one of the conditions at means this is the order of ion flux density and that will be the ion energy if we can have such situation, then we may expect a well adherent, well densed coating without having to much of surface defect and the residual intrinsic stress and that stress may be the result of high substrate voltage, so definitely one should look at the various importunities or possibilities on how to reduce the value of V s and at the same time we can augment this ion flux density, so that a coating with all the desired properties can be produced on this substrate surface.

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Limitation of
Balanced Magnetron


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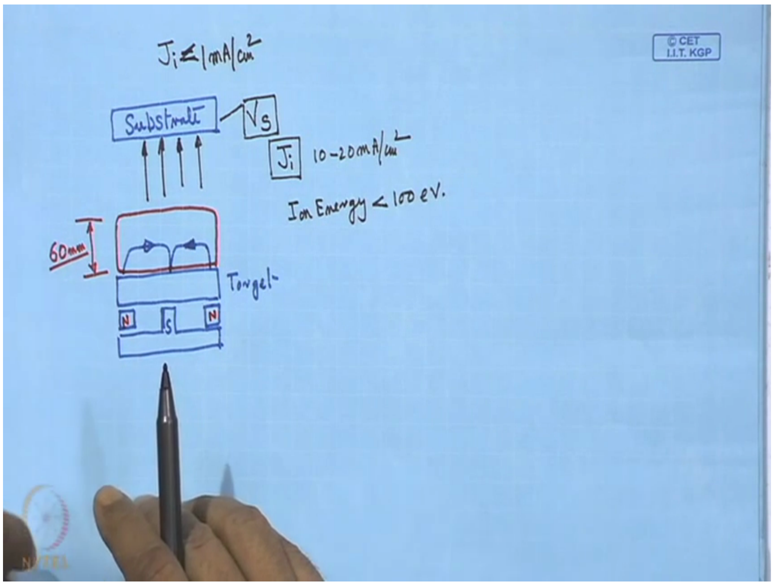
Unbalanced Magnetron



So these are the limitations of balanced magnetron what we have shown in this case and to just minimise or to eliminate this limitation or weakness of the balance magnetron, there came into being this what we know as unbalanced magnetron. Now in unbalanced magnetron in simple terms what we understand that this North pole and South Pole that means the central pole and the ring magnet that means on the ring they are not of the same strength, so intentionally it can be that this North Pole is stronger than that of the South Pole or in can be the other way around that means the South Pole that means the central pole that can be made stronger related to the North Pole.

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Unbalanced Magnetron

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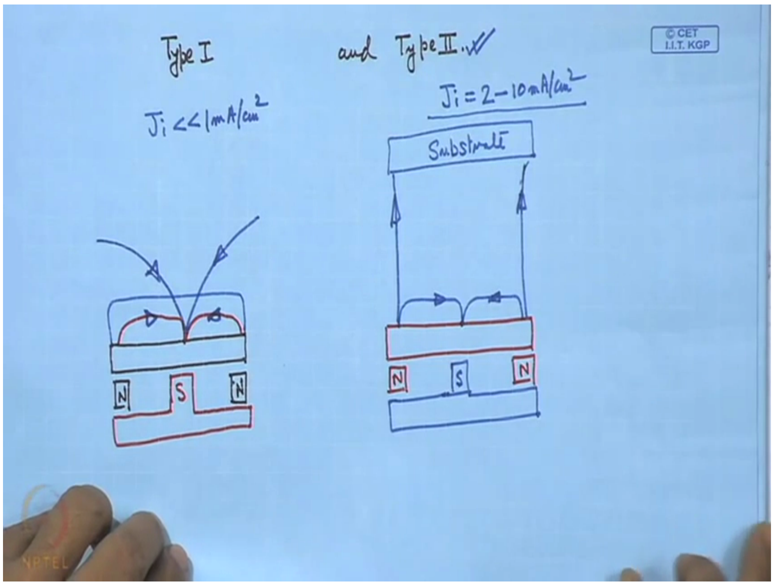
Types of Unbalanced Magnetron



Type I and Type II

$J_i << 1 mA/cm^2$

$J_i = 2-10 mA/cm^2$

Now let us look this unbalanced magnetron, so basically it is actually unequal strength of the 2 poles of the magnet. Types of unbalanced magnetron, there are 2 types we call it type 1 and type 2, so in this what we find that in this type 1 where the North Pole and the central one that is the South this is the magnetic pole piece, so in this case what is important to understand? That all the fields are not closed between these 2 poles, so there are some field lines or lines of force, so these field lines are like this mostly it is connected but since here the South Pole is stronger than the North Pole many will be directed towards the chamber of this sputtering device and that will be something like this, so that will be.

So this is how they are closing but in addition what we have, that few of those lines of force because of this stronger south pole that will move towards this the central one which will be stronger, so many will be directed towards the surface and then they will close themselves on this south pole like that and in this case what we see that in this case type 2 and in this type 2, what we can see, this is North Pole and this is South, so in this case this is stronger, so North Pole is stronger than the South pole, so in this case there will be some of the lines of force which are closing between the North and South, however if we have the substrate here, substrate in that case few of the lines of force that will be directed towards the substrate.

So this will be few of the field that will be directed toward the surface and as a result of that this plasma which is more or less confined within this volume, this is the plasma volume and here that Ji is even much less than 1 milliampere per centimetre square and here it will be more than that, so Ji will be somewhere between 2 to 10 milliampere per centimetre square. Actually what happens along with these lines of force some of the secondary electron which are concentrated here that will also follow this magnetic field and then the whole electron, secondary electron that will be also moved and because of his electrostatic field and affinity ions can also follow that and as a result of this, we can expect ion impingement on the substrate and in this case this ion current density, that will be in the order of 2 to 10 milliampere per centimetre square and we can expect a better property on the coating on this substrate over the substrate and this can be made possible even without application of any substrate biasing.

So this is one of the greatest advantage and can realize when we need to have densification of the coating on the substrate and without having much increase of the substrate bias thereby avoiding incorporation of any substrate defect on the surface and at the same time we can have a densification of the coating having a high value of ion current density, so low energy ion but with high flux density that can be created just by stretching this plasma volume by this unbalancing of the magnet and in this case these ring magnet field strength is greater than that of this central pole, central magnet and this is known as type 2 whereas where we have stronger central pole and that is known as type 1.

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Limitation of Single Target
UBM (Unbalanced Magnetron)

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Now we look into limitation of single target unbalanced magnetron, so what is mean by single target, so as we know that in sputtering can be single target or it can be multi target that means we can have dual cathode facing each other or we can have even 4 target but the simplest one is having just a single target.

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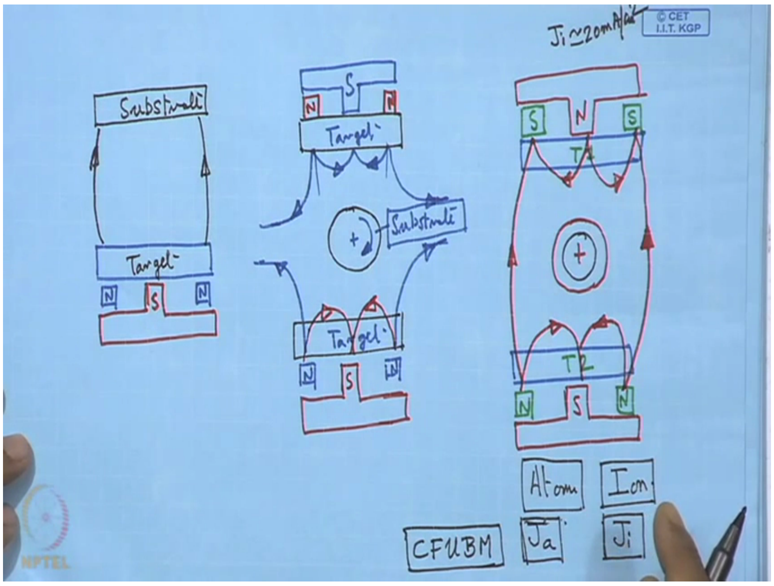

So if we have a single target just like this it is a single target machine where we have north that is the ring and the central one that is the south that is the pole piece and this ring is stronger than the central magnet and here what we see that if this is the substrate, if this is the substrate what we can have? Definitely the plasma can be stretched, it can be directed towards the surface and the it is obviously advantageous in comparison to a balance magnet magnetron, so that is no doubt about that, however the problem is that it is only from one side.

So when we have a substrate with a complex geometry, suppose this substrate is having a cylindrical shape or some 3 dimensional geometry, in that case covering of the substrate with the same uniformity of the coating thickness that is issue number 1 and also having the uniformity on the property on the coating over the inter-surface that is actually one difficult task. Even if the substrate is rotating then what will happen, so in one cycle half of this cycle 1 semi-circular portion one half circle will be exposed to this sputtered flux while the other part will be having a shadowing effect and this will have an immediate effect or influence on the property of the coating, so this has become one of the greatest limitation of this single target unbalanced magnetron.

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Dual Target UBM

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So as a substitute of this single magnetron, single target magnetron now we have a dual target unbalanced magnetron, so this dual target what we have in single term 2 targets facing each other.

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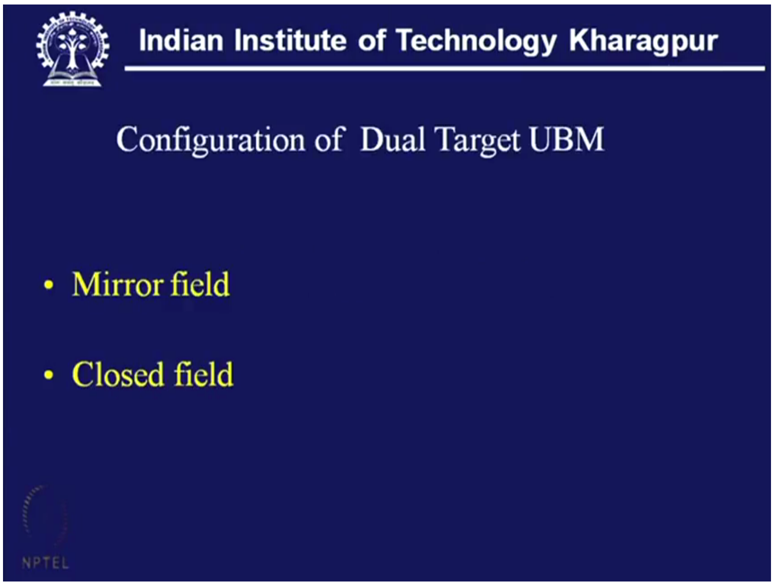
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Configuration of Dual Target UBM

- Mirror field
- Closed field

Now here this dual target magnetron which is of course unbalanced in nature, they are facing each other and we can have 2 configurations, one configuration we call it mirror filled and the other one we call it is closed filled, so one is mirror filled another is closed filled, so let us look what is mean by this mirror filled, so we have twin targets facing each other and in this case we have centrally located the worktable, worktable means here the table for supporting the substrate. This is the table and substrate can be placed and it can have rotation and this can be a single stage rotation, two-stage rotation or even 3 tyres rotation.

Sun, planetary, satellite type of rotation to have better exposure to all geometrical detail all on the all the points on this complex geometry that need to be exposed this ion flux or this sputtered flux, so for that we must have all this mechanical arrangement, so this is one target, so this is one target facing each other so here we have north and definitely the central one will be the South on this one which is placed with its surface facing upward, so it is vertically upward this target, so in this case what is going to happen, so this is South so it will be a field like this, so this is closing north to south but here what we have, we have also north facing north, so this is also a north pole which is the ring magnet and we have a central pole piece that is the south, so this is South and here what we have?

This is also north, south closing the lines of force the field lines, however here this will be rappelling, so this lines of force which will remove like this, so this will be the lines of force which are directed towards the chamber valve, so here north pole is stronger, not pole means the ring magnet that is stronger than that of the central but they are facing they are opposite to each other and in this case the definitely this plasma, this plasma volume within which this is substrate is placed that is not subjected to a plasma volume having a very high density rather it is a plasma volume having a low density and this substrate ion current that will be rather low in this case and as a consequence of this what is expected on the coating which will be deposited from this flux coming from this side and the flux which is also ejecting from this side through dislodgement.

So both the flux will have a low density and the expectedly coating will have a porous structure, so we can also introduce some kind of porosity within the volume of the coating and according to the need of somewhere we need a porous structure for some reason and not a dense structure that can be very easy obtain by this by this arrangement by this option where the north pole of one of the target and which is facing the remaining of this dual system, so they are facing each other. That is why this field of this field lines they are almost like repelling each other and we do not have a densification of the plasma, so this we called mirror filled and this is can be useful where we do not require a intensify coating, a dense coating rather a coating with low density or even porosity.

Now if we consider the other one that means this closed field magnetron, it is in this form, so these are the 2 magnets, 2 targets and just behind we have the North pole that is the ring magnet and here of course it is South, so this is target 1, this is target 2 and configuration is like this North facing south and obviously this happens to be the central pole South and here the central pole is north, so this will be the magnetic flux which will be connected from North South, this is going to be also North South, this one too and at the same time this will be the closing of this lines of force and this will be the closing from this north of this magnetron to the south of magnetron just about this and this is also another close loop.

So this is going to be another closing of this field, this field line and this whole thing is whole area region becomes the plasma volume and if one plays the rotary table and the substrate over this then it is submitted to very high plasma density and this can be as high as Ji as high as 20 milliampere per centimetre square and to achieve this with this arrangement it is not uncommon and with this we can have a very high density coating, dense coating with all the required properties and uniformity of the properties and in this case what we see? That since it is rotating and we have 2 targets from 2 sites, so maintaining the uniformity of the thickness and uniformity of the property would be less difficult than in the case where we use just one single magnetron.

So the main task here is that, how we are going to make this unbalancing is? So the whole task is like that, that near this substrate surface we like to increase, we must increase this ion current density and what happens exactly at the substrate surface actually the atom of this target material that is incoming, so this atoms are arriving on the surface, however at the same time ions of this argon or this discharge gas that is also arriving.

So we may look into 2 parameter one is called this Ja another is called Ji that means the flux of atom and flux of ions both are important in that when atoms are arriving on its face they will form an arrangement and that will form one into that will come in the form of for coating but it is same time the whole idea here is to have a flow of this ion and this ions are stretched, they are pulled from this from this surface of the target more towards this surface because this ions are supposed to strike this target surface but here what we are doing just by pulling the secondary electron and by closing this one, so this is called actually a closed field unbalanced magnetron sputtering, so it is what we can say this is actually closed field unbalanced UBM, so it is actually the closed field unbalanced magnetron.

So here are the fields are just not like open but it is a closed field and this this closing of the field is possible just by having 2 targets which are facing each other and having some magnetic coupling between these 2 are a proper placing an arrangement of the North and South or the ring and the pole magnet in this case. So what we find that this Ja and Ji both are important and along with Ja 1 to also pay attention to Ji that means the ion flux density because this ion flux which is arriving on the surface of the coating on the substrate, this ion flux impingement will actually change, modify the structure according to the need of functional requirement, so functional requirement will be well served by this coating provided we can get the desired property on this coating and in this respect this ion flux density that is one of the important parameters in the whole process.

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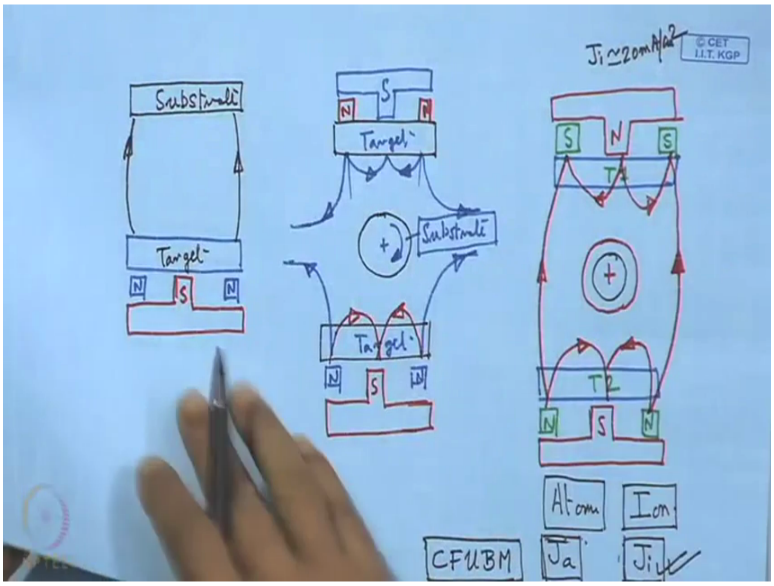
Dual Coplanar Target CFUBM



Now comes a dual co-planer target closed field unbalanced magnetron, so it is a dual co-planar target, so it is a dual target but both are lying in one plane. As we have seen clearly in this case they are facing each other but we can have another configuration where these 2 targets can face each other.

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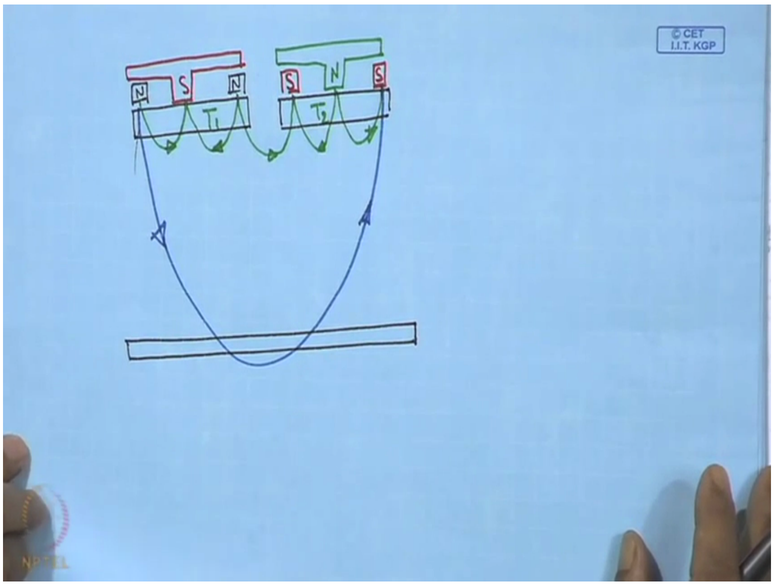

So this is one target and we have another target like this and this is also a magnetron type source. This is north this is a ring and then we have the pole here central one South and this is going to be now South, this is going to be South and then what is going to happen, we have this one as this the Central one that is going to be the north and what we can have here that this will be the coupling between North and South, there also are coupling between the 2 magnets of the 2 adjacent cathodes.

So this is the coupling and apart from that we have a coupling between North of this left-hand side target 1 and this is T2, so this will be another coupling this way, this will be another coupling and here what we can have? We can have a plane target it is something like this, so it is well placed within this plasma volume. So if we have a large piece which need to be coated in that case we can have a large plasma volume or which in which the substrate can be placed or we can have 2 materials and they can be properly combined to form one alloy or a graded structure on this flat large surface and this is a dual target lying in the same plane and having a closed field unbalanced configuration.

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Dual Target Barrel Coater with CFUBM

Now this is very interesting device this is called a dual target barrel coater and it is having this closed field unbalanced magnetron configuration, it is a dual target configuration with closed field unbalanced magnetron and this will be used for very special application, so here what we see that this targets which are in the previous case they were lying in one plane.

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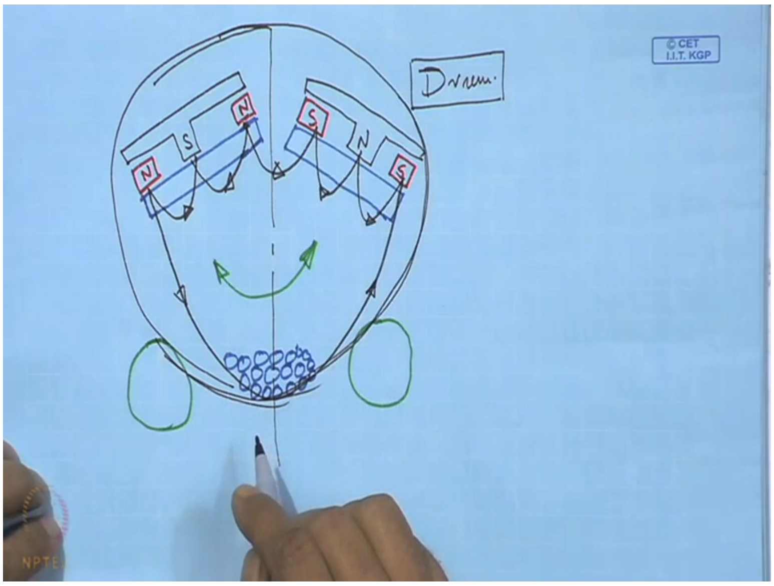

But in this case they are oriented in a form having some inclination related to one another, so it is just that inclination between these 2 targets and what we have? This is North, this is also…so this is actually South, so magnetic coupling will be made here and we have this ring, this pole which is South this is the ring and here we have the Central magnet and this is going to be the North, so it will be also similar coupling, so only that change what is taking place here, we can see so it is this way coupling is made, so that is North to South but at the same time what we can see here this is going to be another coupling like this, so it is not to South and here what we can have a barrel coater means we can put a tumbler.

It is like a tumbler so it is like a drum and which will be provided with a it is a drum or barrel and which will be provided with a tumbling motion, so in fact what we can have in this case, this is going to be a barrel, so it is going to be barrel and this barrel will be supported on 2 rollers, so this whole barrel will have a tumbling motion like this, oscillatory motion and this surface that is well within this plasma volume is positioning is very important in this case so that we can have an active or a useful surface on this barrel where we can safely put some grain like particle or it can be ball or it can be grain or something like that and it will have a tumbling motion and with that what we can have, we can have a coating on grain like thing, on small pods maybe the balls of the ball bearing or small mechanical component and by this tumbling motion and with this barrel platter we can also have is closed field unbalanced magnetron configuration and with this we can have just coating on the small parts.

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Multi Target CFUBM

So it is actually a multi target closed field unbalanced magnetron sputtering and with this multi target sputtering instead of 2 targets here what we can use, even we can go up to 4 target and that is one of the commercial applications of this unbalanced magnetron sputtering.

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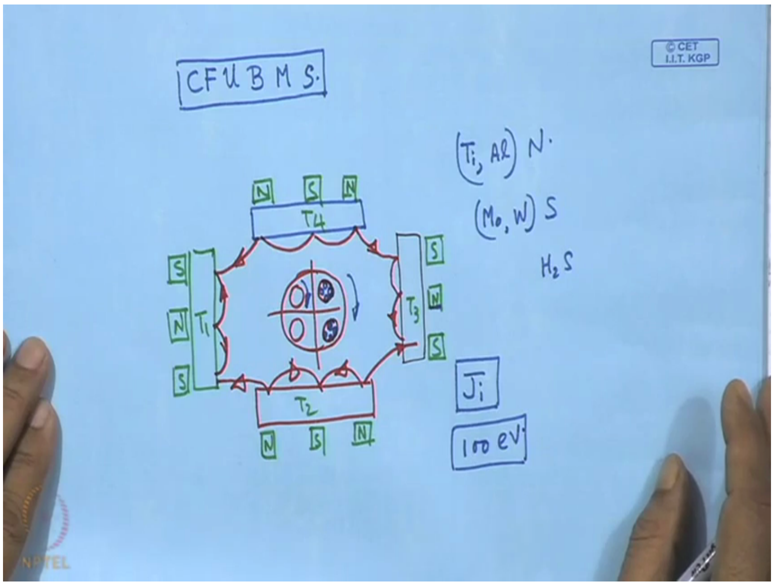

So it is actually closed field unbalanced magnetron sputtering and let us have a look how this targets are placed? So this is going to be one target and opposite to this another target is placed then at right angle we have one target and on this side, so these are the 4 target machine T 1 and T 4, 4 target machine so obviously here we have see this North South and there must be proper unbalancing between these 2, so this is going to be north and this is central one to be South and accordingly we have 2 have this kind of arrangement and then we must have this coupling, so how it is done?

So it is going to be something like this, so this is North to South, this is also North to South, this is another coupling, so this is magnetic coupling, there also the magnetic lines of force are closed, closing themselves so this is another coupling here, so magnetically the all the magnetrons are connected magnetically, so we get a huge plasma volume and within that what we expect, we expect to have a plasma volume with density, high density and uniformity of the density and in this case we can, one can put a rotary table on the surface and with that we can have large volume of parts, so this is just the top view and with this top view what we can see?

This can be quite long this is like a cylindrical table, we can have 3 stage rotations that means here we have table, so these are the small…so this is almost like a large stable then on that we have the planet and over that we can also have satellite, small satellite that means we can put 4 satellites just like this, so we have 3 stage rotation this is one rotation, this is the rotation of this planet and then you have the rotation of this satellite, the blue one, so with this 3 stages we can ensure quite good uniformity on the various complex part of any machine component and in this case it is just not a metal coating, it can be one alloy, it can be one compound, we can also have a graded structure say for example see if we are interested in in say for example titanium aluminium nitride or we can have molybdenum tungsten sulphide, something like this.

So in this case what we can have? We can have titanium targets and aluminium targets suitably arranged or molybdenum and tungsten target that can be also placed here and through this reactive sputtering which already we have mentioned, we can have this reactive gas either in the form of nitrogen and for sulphur we can have H 2 S it can be any carbide, it can be any compound of some of the strategic element and they can be mixed here just by coupling this targets magnetically and here most important thing is that, that is plasma density, plasma density or say substrate ion current density, substrate ion current density, so this is one of the very important parameters, so far as the ion flux which is arriving at the substrate surface is concerned, so definitely one should look at how this unbalancing can be made, what is the efficient way of doing this unbalancing?

Then we have the fixed unbalancing then the whole process has some restriction in in conducting the process and when we have some kind of flexibility that means either by using one electron magnet, we can have variation in the field strength of this North South and thereby we can vary the degree of unbalancing also just by adjusting the position of this North or South with respect to this target surface there also we can have unbalancing and this unbalancing will determine that what will be the ion flux which may be available on the substrate surface which will be useful in having impingement or showering on this material which is condensed on the surface of the substrate and at the same time with this ion flux density which is Ji and its strength which should be and its energy which should be kept well within this electron volt, so this high flux density with a low energy well within, so this is the one of the prime objective or goal of making this unbalanced magnetron system so that ultimately the desired outcome that can be produced and we can get one of the best coating available for functional purpose.

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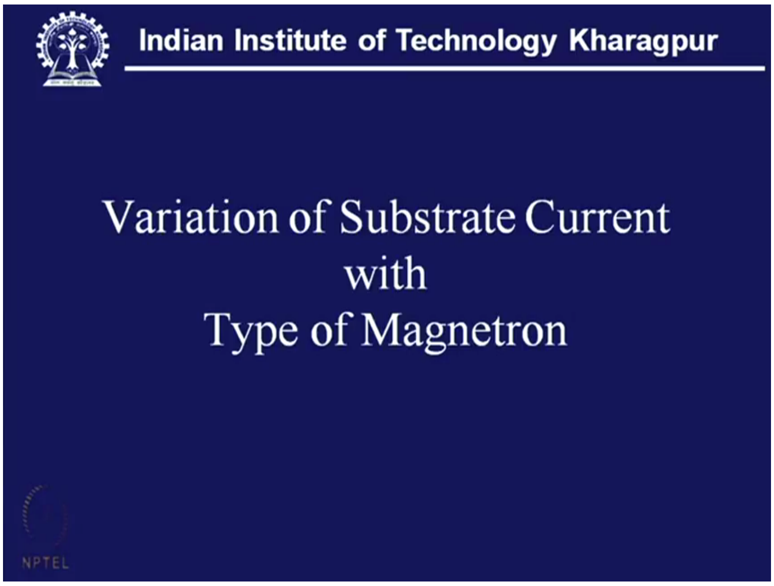

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Variation of Substrate Current
with
Type of Magnetron

Now it comes variation of substrate current with type of magnet with the type of magnetron, now this is this graph is one way very important because it gives us lots of information about this efficiency of this unbalancing.

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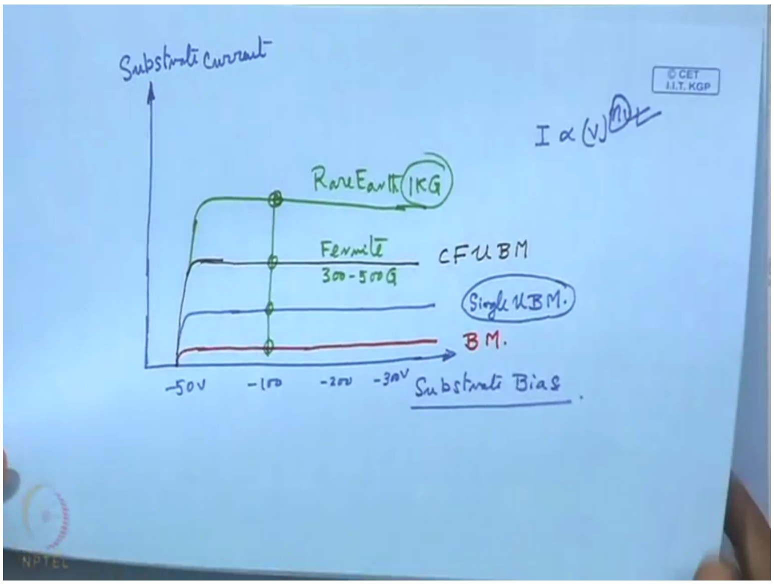

As we know for a magnetron and this is very important relation V to the power n and the value of n is actually the index of performance of the magnetron but here what we measure, we measure actually the substrate current, substrate current and there it is actually the substrate bias, substrate bias. So one would expect a high substrate current with a low substrate bias, nor in this case what we can find? We just one ordinary with an ordinary conventional magnetron a very low weak signal that one can capture out of this substrate surface, it is a very low value of substrate current with a conventional or a balanced magnetron.

So in this case obviously one to go for a better arrangement how to extract or how to extract more current or how more number of ions will be directed towards the substrate. So in this case if one go for a single target, single target it is a single unbalanced UBM, single target unbalanced. Their what we can see it has it can improve a lot but what is very interesting thing to know also that if it is minus 50 volt, 100 volt or minus 200 that means increase the increasing the substrate bias will not give any positive results so far as substrate current is concern it gets saturated very soon, so one objective will be to have an alternative method and how to generate more substrate current.

So lots of time has been already made and the outcome of this we can see just by augmenting this current and this is actually close field UBM that means close field unbalanced magnetron and it can be a twin or it can be 4 target but what we can see, what we can see that in this case the substrate current is already increased quite substantially. Now with further research it could have been raised further, so in this case one can see that it has been raised further, so these are all the results of research, so from this point to arrive at this point for a particular voltage even if we consider this voltage out it could have been increased, so here this is closed field unbalanced magnetron.

So it is by unbalancing and here what we see it is actually the material of the magnet, so it is actually a ferrite magnet, ferrite magnets and this ferrite magnet has a field strength of may be 300 to 500 Goss G but when it was replaced by rare Earth the field strength, so it is a better material and so the field strength could have been raced to 1 kg Goss, so definitely this field strength helps in improving these substrate current and this is one of the goal of this research and the activity concerning this unbalanced magnetron system or the resource how to increase these substrate current without increased of these substrate bias.

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Structure Zone Model
for
CFUBM Sputtering

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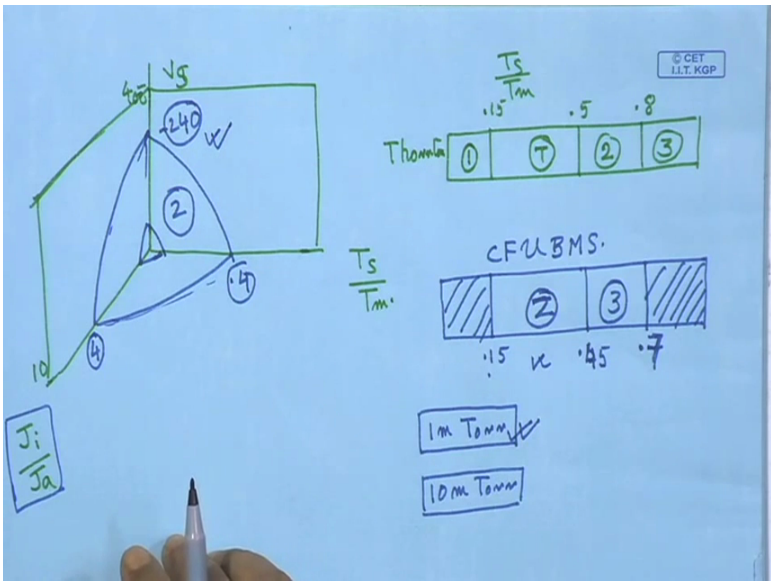

So it is actually structure zone model for CFUBM sputtering, now here what we can see that if we have a three-dimensional presentation then we can have a look here that this side we call it T s by T m that is homologous temperature melting point of the target and the temperature of the substrate, this side what we call that is the bias voltage of the substrate and this side very important thing is Ji by Ja that means influx of ion by the influx of the atom which is arriving on at the target surface. So here what we can find maybe this is around 10, 400 and this is 1, so we can have such kind of a rectangle but if we consider the zone structure, zone model following the Thornton diagram, what we see here 0.15 this is T s by T m and then we have about 0.5 and then about 0.8 and this is zone 1, this is zone transition zone T and this is zone 2 and this is zone 3 and this so this is according to Thornton diagram.

So this is normal sputtering very conventional sputtering but when we have this unbalanced sputtering, we have another map and in this map what we find this is 0.15 and then what we find within this 0.5 up to this 0.5 what we get it is about 4.5 and within this 4.5 what we get it is actually the zone 2 and what we have here this is actually 0.7, so this is actually 0.7 and here what we have zone 3. So what we find here that with this low temperature within this range we get a structure having zone 2 which is a dense broomstick structure and this is possible by CFUBM this is possible by this close field unbalanced magnetron sputtering and here within this zone low deposition was done even after the beyond 0.7 there was no attempt to make any deposition.

So you one can compare with this one which is a conventional way of doing the sputtering and another is with close field unbalanced magnetron and what we can draw your quickly that this is actually the zone where we have this is having 4, this is 250, 240 and this is around 0.4 and this is a small zone where low deposition has been done and this area well within this blue line confined by this 3 lines blue and this green line of the axis that is actually zone 2, so what we find that T is totally absent and we get zone to straightforward directly and with this 0.15 to 0.45 with this low temperature and the pressure what can be just one millitorr which can be so sufficient to carry out that sputtering which could have been at least 10 millitorr.

Had it been conventional magnetron sputtering, so with this unbalanced at least one can find the advantage in this zone structure which we can achieve at a low sputtering temperature low-pressure and here what is important that this Ji by Ja that means influx of iron by influx of atom, that has to be increased and that is responsible or lowering the requirement of pressure, temperature and the substrate bias.

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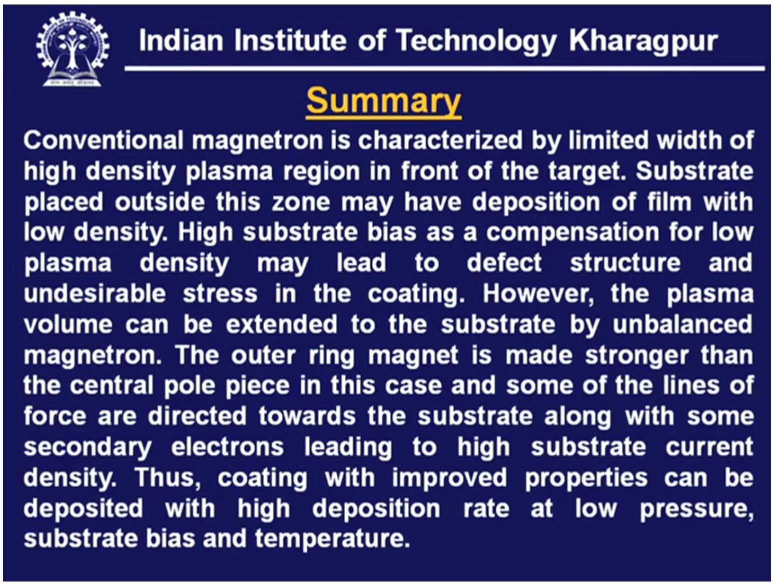

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Summary

Conventional magnetron is characterized by limited width of high density plasma region in front of the target. Substrate placed outside this zone may have deposition of film with low density. High substrate bias as a compensation for low plasma density may lead to defect structure and undesirable stress in the coating. However, the plasma volume can be extended to the substrate by unbalanced magnetron. The outer ring magnet is made stronger than the central pole piece in this case and some of the lines of force are directed towards the substrate along with some secondary electrons leading to high substrate current density. Thus, coating with improved properties can be deposited with high deposition rate at low pressure, substrate bias and temperature.

So with that we can make a summary conventional magnetron is characterised by limited width of high-density plasma region in the front of the target. Substrate placed outside this zone may have a deposition of flame with low density. High substrate bias as a compensation for low asthma density may lead to defect structure and undesirable stress in the coating. However the plasma volume can be extended to the substrate surface by unbalanced magnetron. Here the outer ring magnet is made stronger than that of the central pole piece and some of the lines of force are directed towards the substrate along with some secondary electrons leading to high substrate current density. Thus coating with improved properties can be deposited with high deposition rate at low-pressure, low substrate bias and low substrate temperature.