Introductory Neuroscience & Neuro-Instrumentation
Indian Institute of Science, Bangalore
Lecture No. 58
Physical Vapour Deposition E-beam Evaporation

Hi, welcome to this particular module. In the last module we have seen thermal evaporation system and in fact we were discussing about thin film deposition and in thin film deposition or it is also called vacuum deposition because we require vacuum to improve the mean free path that is the atoms before it collides to the gas molecule inside a chamber, so if you have a mean free path which is longer the deposition would be better, so for that you have a higher, you need a higher vacuum and because the deposition occurs in vacuum it is also called vacuum deposition technique.

So, now when we talk about thin film deposition we also discussed about 3 different techniques, the first one was thermal evaporation, second one was electron beam operation and third one is the sputtering. Now, all 3 techniques are physic, comes under physical vapour deposition techniques.

Now, we further discussed that the thermal evaporation and e-beam operation are the electrical way of depositing the film while sputtering would be a mechanical way of depositing a film. What do you mean by the electrical wave, what do you mean by the mechanical way, we will lo in the into these lectures further. If you recall in thermal repression what we do, we have a board or a source on which we board in which we load the source.

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For example, this is the metal that I want to deposit, I will load on the board and then I will heat it right by applying a high voltage. Now, because this is a metal board what will happen when you apply voltage because there is a metal, metal as a low resistance, the flow of current is extremely high and that is why I square R heat will be generated this will start heating, when my board starts heating or the holder for the source are heating the source inside the holder also starts heating.

And when it starts heating because the source melting point that is this black dot that melting point is lower compared to the board that is the holder this will melt first and will start evaporating, while the board will not be affected. The difficulty or the limitation in the thermal evaporation is that when your source temperature that is this black dot its temperature is a melting point is extremely high or is equal to the holder temperature.

That means, if I heat it this will not melt until it reaches temperature which is equivalent to it or it requires higher melting point than this, so that is the difficulty because then in that case the holder will start evaporating we do not want holder to get evaporated, we only want the source inside the holder to get evaporated that is why this holder is also called source holder, this is a source which is a black this button in my hand and this is my hand itself this palm is my source holder, source holder melting point should be extremely high compared to the source that is holding it.

So, what is done, how we can overcome this limitation? Now, what kind of materials would have such a high melting point? So, example is silicon dioxide, example is silicon nitride, bsg and psg and lot of other films are there that we can grow, but it cannot grow inside the thermal or using the thermal evaporation.

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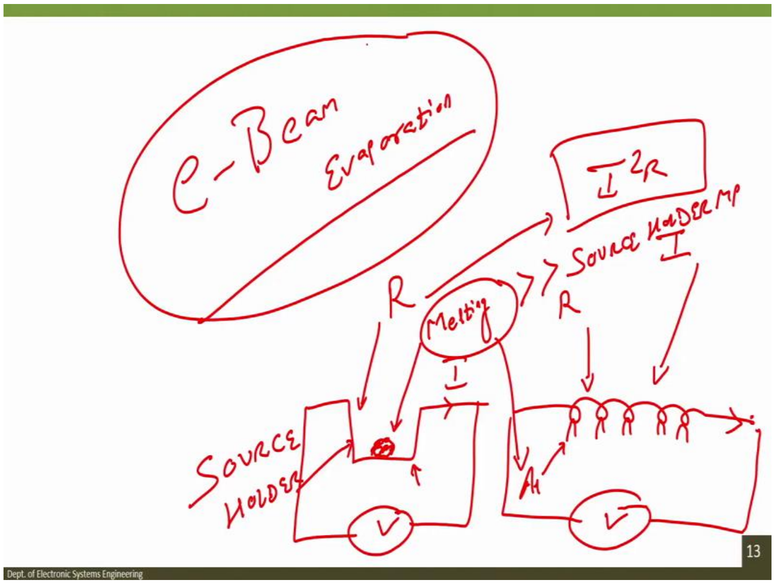

So, if you see here in the slide, today we will be looking at electron beam evaporation and in this case you see this is what I was talking about source holder, source holder in which this button that I was showing let us say it is like this. We can also have source holder like coil, like this, and let us say we want to deposit aluminum, then this aluminum wires would be loaded onto this coil like this. So, what will happen if I apply a voltage through this particular coil or across this coil what will happen?

There is a flow of high current I, and because of that the resistance here is R and that would be I square R heating which will heat up the aluminum wires that are loaded onto this particular foil or coil. In this case same thing if I apply a voltage across the board because of high flow of current because this is a resistance it is a metal, I will be extremely high so again there will be I square R heating and this will start heating up and the source inside the board will start melting. In this case, aluminum is our source, in this case also we can have aluminum chunk or we can have other metals that you want to deposit. This is the principle of thermal evaporation.

The difficulty comes when the melting point of the source is extremely high compared to the source holder melting point that is a difficulty. So, to overcome that difficulty we go for electron beam evaporation and then we will see how this electron beam evaporation helps to overcome this particular limitation of the thermal evaporation or posed by thermal evaporation.

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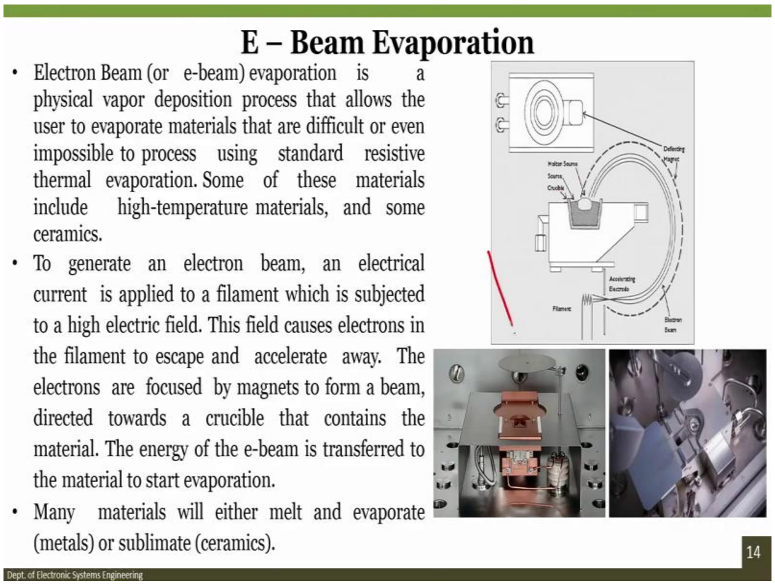

So, what is electron beam evaporation? Electron beam evaporation is a physical vapor deposition that means PVD process that allows the user to evaporate materials that are difficult or even impossible to deposit using standard thermal evaporation technique. So, some of these materials include high temperature materials and some ceramics.

Now, if you see here, this is a schematic representation of how the electron beam will help to melt the material that is loaded inside the source holder. Understand that in this case we cannot use the metal board that we are using earlier, in this case because we are not heating this board, we are using electron beam to directly, this is a, so in this case this is called crucible, crucible and there can be quads, so quads has extremely high melting point.

Inside the crucible we will load up let us say material and the electron beam as you can see here I will come to the point that electron beam will hit this particular source and the source will start melting and it will start evaporating. So, since the electron beam is at extremely high temperature is a focused beam it will melt the source material.

So, here you can see here this is an electron gun through which the electrons are, this actually reflection magnet, I am sorry, this is a electron gun here this is a filament so through which the electrons are incident through the accelerating electrode, accelerating electron will accelerate the electron beam further and then there is a deflecting magnet which is here, so this deflecting magnet will help the electron to deflect and to be incident on to this particular source. So, when the electrons beam is deflected and incident onto the source the source will start melting and once it starts melting it will start evaporating.

You can change the amount of deflection and you can use a different way of evaporating that is called point way of evaporating that means the, so the electron beam will only point at one place which is let us say here, in other case it will go for a scanning, it can be raster scan it goes like this, it can be triangular wave so it can be do like this. So, there are different way of evaporating the material each has advantages, disadvantages, you do not worry about that too much, right now we understand that electron beam will overcome the limitation posed by thermal evaporation as electron beam will directly melt the source which is loaded onto the crucible.

So, what you see here there is a shield, it is called shield, was a use of this shield that until the man, until this source, see what happens is let me go to our previous slide and let me just show it to you. Let us take this example it is easy because we have already drawn here. So, in the case of why you require that shield, I will show it to you just bear with me for one second.

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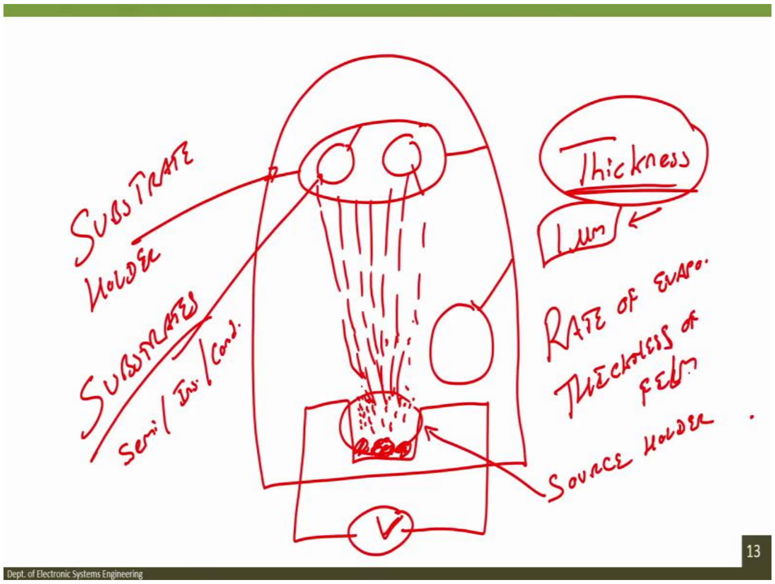

So, now you have a chamber and here you have your substrate holder and on this substrate holder you have loaded let us say two silicon wafers. And then this is your metal, let us say it is aluminum and you are going to heat this source holder by applying a voltage V. Now, when you start heat, when this source holder starts heating this will start melting and it will start evaporating.

But we want to know what is, we want to actually have a repeatable thickness of the film, repeatable thickness that means that every time I want 1 micron, it should not be one time one micron, one time it might be 1.1 or one time it can be 0.9 this is not what I am looking because that is a very big difference of 10 percent. If I have 1 and if I have 1.1 or if I have 1 and if I have 0.9 it is a difference of 10 percentage which is very big difference or very big error that is why I want every time my thickness to be 1 micron.

So, what can I do, once I know that, so there is a shield here. So, when it starts initially melting know, the only it will deposit on the shield, it will not reach on your substrate holder, this is substrate holder and these are your substrates. Now, if you remember our previous lectures you will understand what a substrate. Substrate can be semiconductor, substrate can be insulator, substrate can be conductor, anything, anything on which you are going to deposit a metal or a material to form a device or a film is your substrate, base material.

So, right now also one more thing is how would you know what is the thickness of your material, when you deposit a material, how would you know it will reach that particular thickness? So, first is that you will not open the shield until this starts melting properly, once it is melting then you will open the shield, when you open the shield what will happen that it will start so when you open the shield, let me just you bear with my drawing let us say the shield is open now.

So, you can the, hence the material will start depositing on to your substrate like this. But before that I also want what is the thickness and what is the rate of evaporation, what is rate of evaporation? And another one is thickness of film, thickness of my film and rate of evaporation that also I want to know. How would I know?

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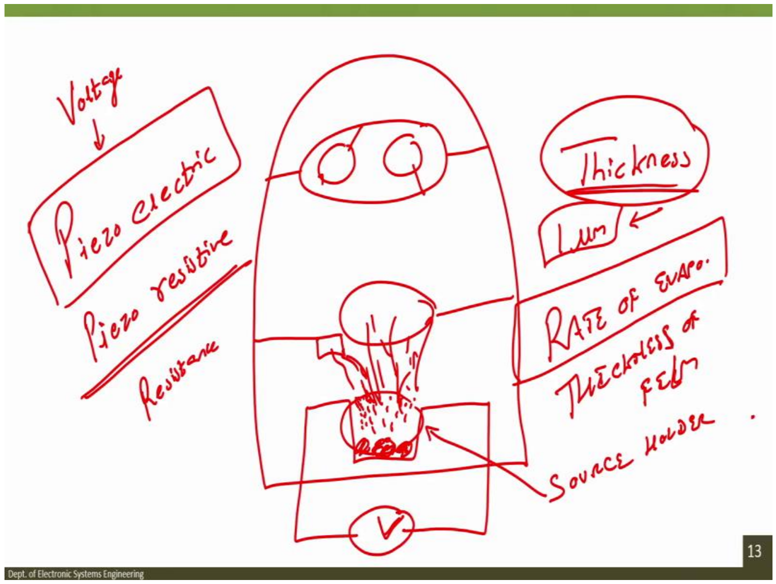

So, there are, before we open the shield, before we open the shield, there is a quartz crystal on which this deposition will occur along with the shield and this quartz crystal will tell you what is the rate of evaporation. How it will tell you what is the rate of evaporation? Because if you know quartz is a, quartz is a piezoelectric material. Now, see sometimes I ask very simple questions even in the interviews and people are confused between piezoelectric and piezoresistive. What is the difference?

In piezoresistive when you apply a voltage there is, or when you apply a pressure there is change in resistance, in piezoelectric when you apply a pressure there is change in voltage. Difference, piezoresistive and piezoelectric difference is when you apply a pressure there is change in resistance in case of piezoresistive, while in case of piezoelectric when you apply a pressure there is change in voltage.

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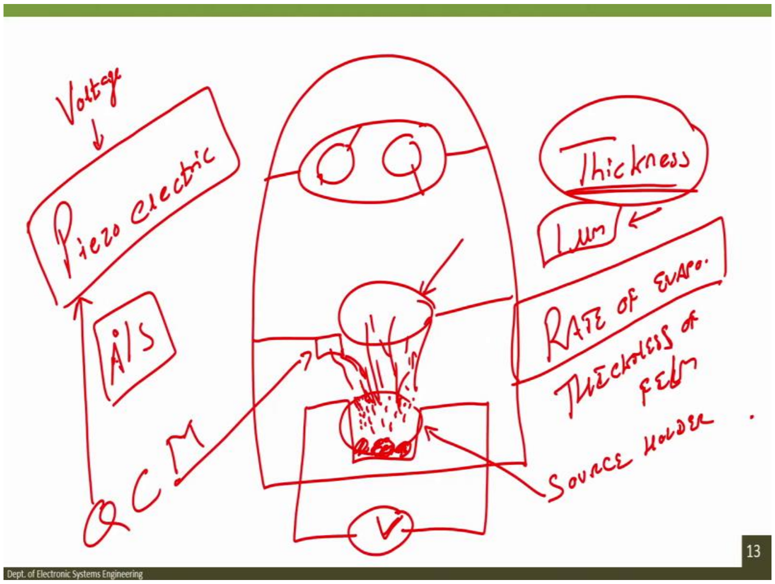

Now, quartz, quartz crystal I said what we have here, quartz crystal monitor QCM, quads stands, Q stands for quartz, C stands for crystal and M stands for monitor, so we have a quartz crystal monitor inside the vacuum chamber to know the rate of deposition, once you have a rate of deposition then you can open this particular shield and let the material deposit on the substrate. This quartz has a piezoelectric property. That means if there is a deposition of a material onto this quartz crystal there is a change in the voltage and that voltage is corresponding or already the parameter is set in such a way that we know what will be the change in voltage for particular thickness of the film.

So, this goes to the electronics which is already fed the change in the voltage versus deposition rate. So, depending on how fast it is depositing, your rate of evaporation would change that means it could be angstrom per second. Generally rate of evaporation is given by angst in the unit called angstrom per second. So, we know the rate of evaporation.

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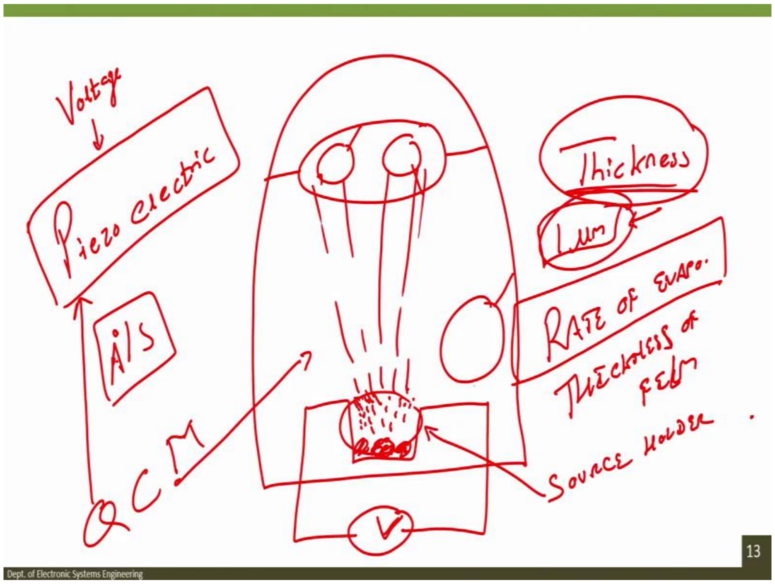

Now, if you know the rate of evaporation that means that when you open the shield when you open the shield, then this will start depositing, when we start depositing what will happen? When we start depositing what will happen? That the substrate, that will be deposit on the substrate. Again we want to stop after we reach 1 micron.

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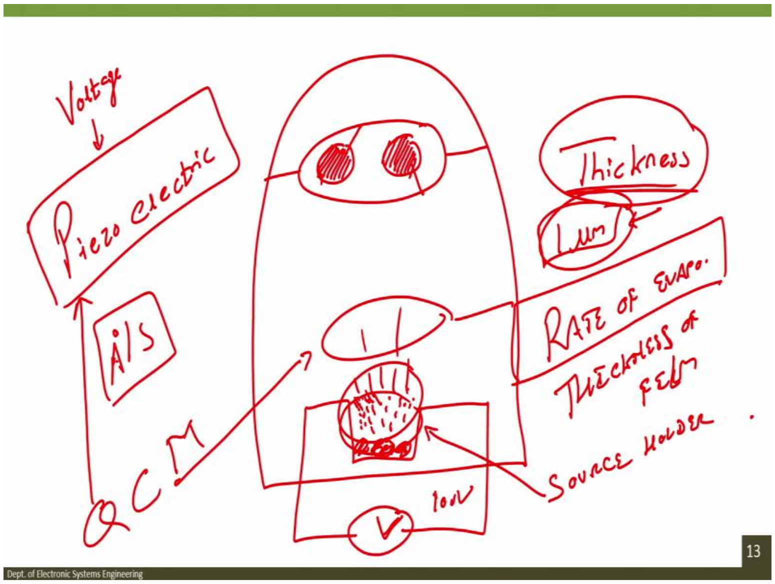

So, to show stop it as soon as it reaches 1 micron we will again put the silt back so that even this because you see when it is at high melting point it will not suddenly cool down, it will take some time to cool down if we make the voltage we bring the voltage back to 0, from let us say 100 volts if I bring back to 0 it will take some time for the material to cool down, so it will keep on depositing. But if I have reach 1 micron I do not want further deposition so this shield will stop the deposition onto the substrate further as soon as I reach my optimized thickness of the material.

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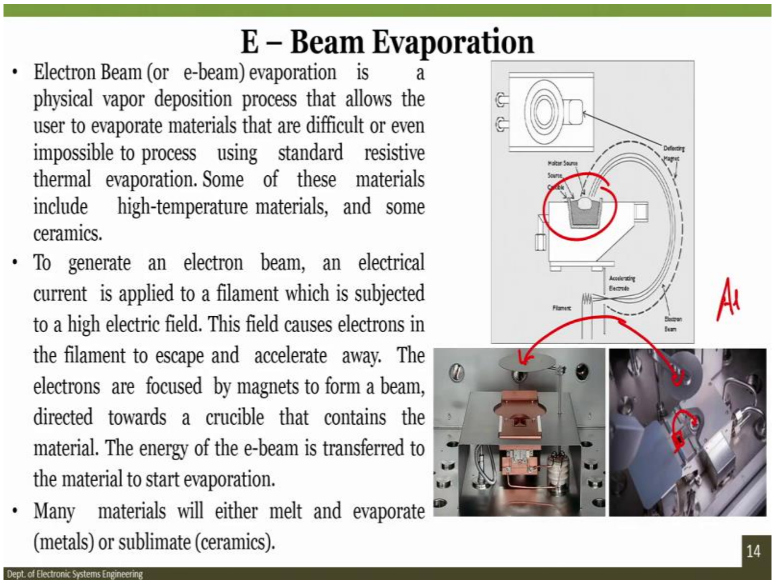

So, there is a way to, there is a way the shield will help and that is the role of shield it is there in so this is shield for source that can be shield for substrate as well. So, having said that what are other things here that you can use, you can see here, you see here that the electron beam will see, I will show you this particular picture focus on this.

Again you can see the shield in both the cases the shield is here. In this case the electron beam will come here and it will incident on to this particular source. So, if I if I delete it you will be able to see that this particular area, you see there is a aluminum here, you can see it is aluminum here. And this hole that you see here that is through which the electron will come and will be incident on to this aluminum material.

And then there are electronics related to that and then the substrate is cooled because you see the this crucible will also get heated up, so you have to cool down the crucible so there is a way to cool down the crucible from the backside using water at a low temperature or a cool water that is flowed across the crucible.

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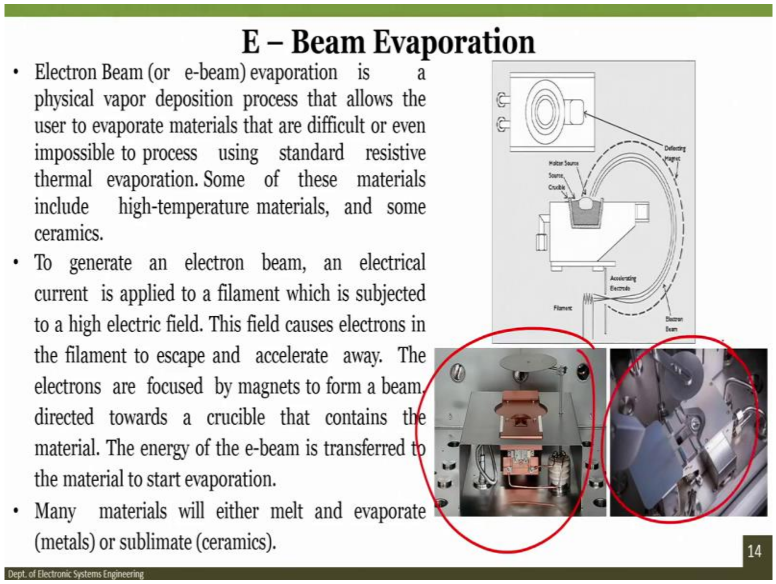

I told you about the, and these photographs are within the vacuum chamber, these are from within the vacuum chamber. Now, one more thing that I wanted to tell is that to generate this electron beam what we require? We require electric current that is why this is also called electrical way of depositing a material. In thermal evaporation also we require voltage and in this case also we require an electric current that when we applied to the filament to generate the electrons and to generate a high electric field and this field what will cause?

The field will cause electrons in the filament to escape and since there are accelerating electrode it will help to accelerate further. The electron beams then will be like we discussed will be focused by magnets to form a beam and direct it towards the crucible that contains your source material.

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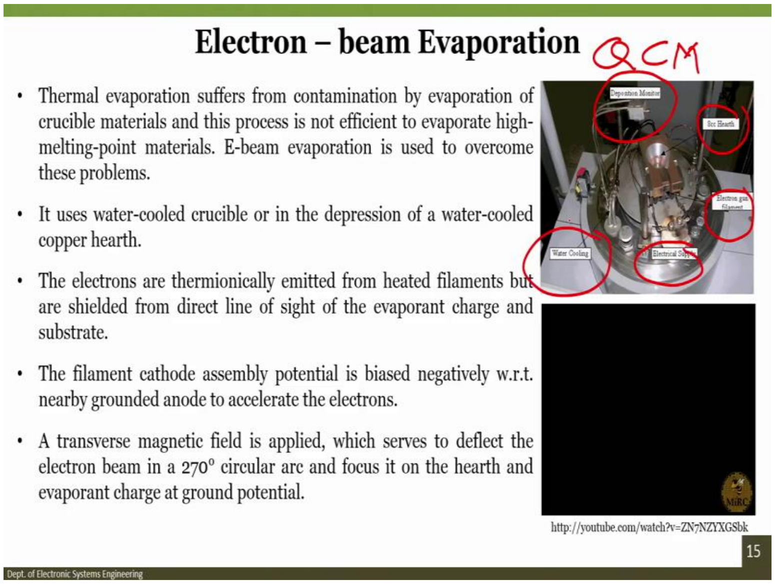

Let us go to this next one and you will here able to see that different things are there, you see deposition, you can see here this one very clearly, this is your deposition monitor. What is that? Now, you know the secret. What is it? It is a quartz crystal monitor QCM. Then this is a 8cc Hearth which is help to hold the crucible. Then there is a electron beam filament, there is a, there are electrical supply and as I told you we require water cooling to cool down the crucible.

Now, if you, what is written here let us read it. Thermal evaporation suffers from contamination by evaporation of crucible materials and this process is not sufficient to evaporate high melting points, material we already know this. So, electron beam is used to overcome these problems and we know how it can overcome now, it uses water crucible or in the depression of water cooled copper hearth.

The electrons are thermionically emitted from heater filaments, but are shielded from direct line of sight of the evaporation charge and substrate. The filament cathode assembly potential is biased negatively because then it will reflect the electron and deflect the electrons further with respect to the nearby anode. Anode will attract the electrons towards it and that is why it will accelerate it further.

The magnetic field that is applied will help to deflect the electron beam all the way to 270 degree centigrade, 270 degree circular arc it is not centigrade 270 degrees this is the deflection we are talking about and focus it on the hearth and evaporation charge at ground potential. If you just want to quickly see the video let me play the video and then you will be able to see.

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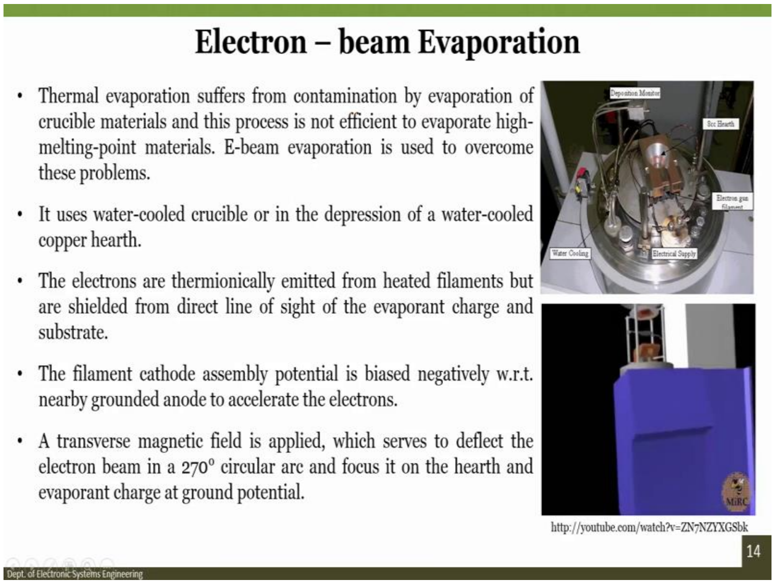

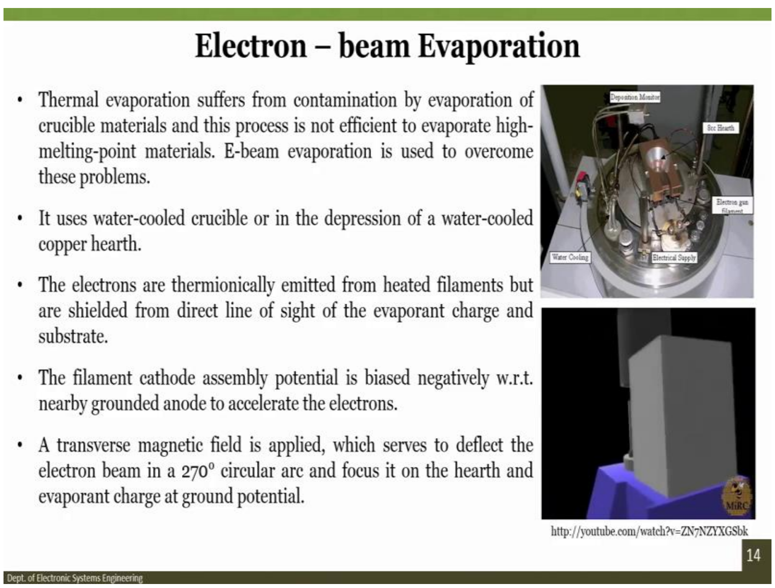

Electron – beam Evaporation

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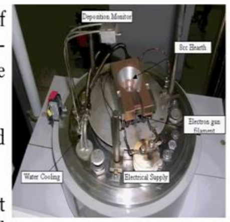

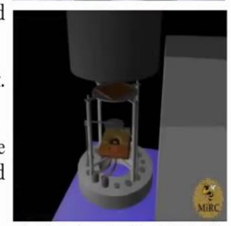

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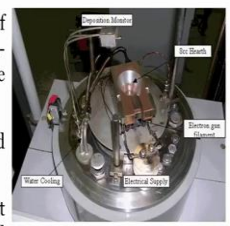

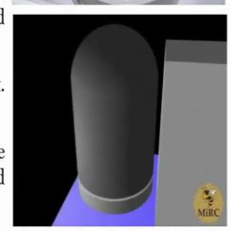

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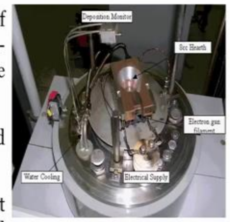

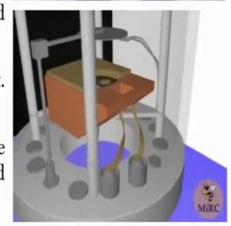

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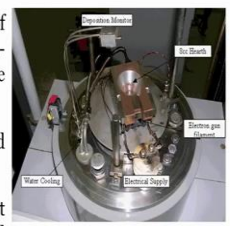

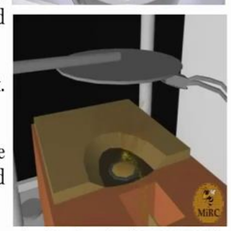

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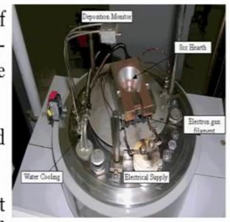

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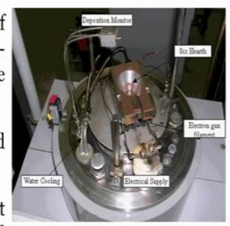

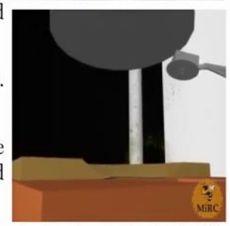

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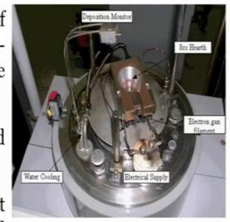

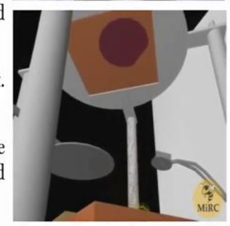

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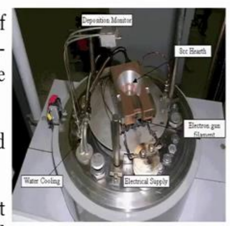

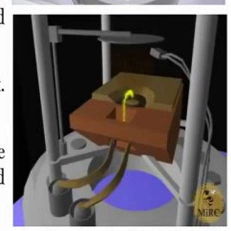

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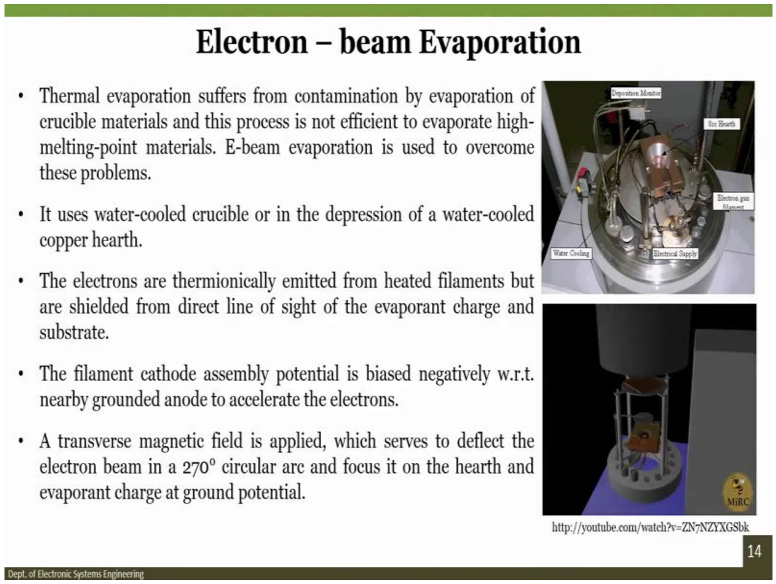

Electron beam evaporator, it is a type of physical vapor deposition tool is used to cut one side of a sample with various metals. Commonly used metals on this machine include aluminum, platinum, gold, chrome, nickel, copper. Once a sample has been loaded the chamber will be closed. The chamber is then pumped down to a very low pressure. The machine then releases electricity through a filament. Several magnets are used to direct the electron beam from the filament to a crucible containing the target metal. The metal then heats up and begins to evaporate onto the shutter. This process can take several minutes.

This is similar to a pot of boiling water on a hot stove. A sensor within the chamber is used to determine the current rate of evaporation. Once the desired rate is reached the shutter is open and the sample is exposed to the evaporating metal. The desired rate of evaporation and the amount of metal to be evaporated can be set under the deposition controller. Once the desired amount of metal has been evaporated shutter is closed. The pressure inside the chamber is an increase to atmospheric pressure and the chamber is opened.

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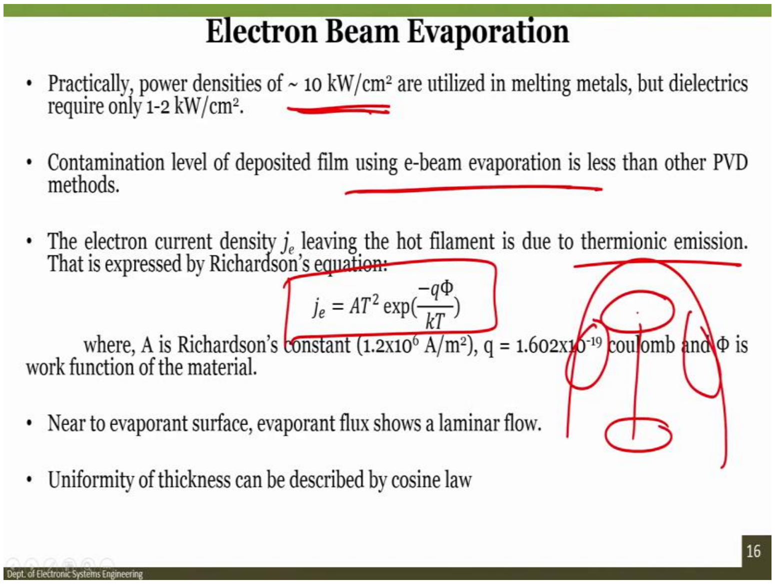

So, what you see, what we are able to see is how the electron beam evaporator work in the last video you were able to see how the electron beam evaporator work. Now, let us further see that what are the power densities and what are the equation that are responsible to generate this electron field and finally for the thermos ionic emission and also we will see that how the evaporative flux has a laminar flow and so and so forth. This little bit of fundamentals that you require to understand not just a system that is there but what are the fundamentals or equations that rule the or that are responsible for operating this particular system.

A physics of it, a science of it is always important for the engineer to understand not just the engineering portion but to take science along with engineering and to make a further device. So, when you use any system try to understand the chemistry or the physics or mathematics the equations that are responsible for the system to work. And then comes the next part what is engineering drawings and to make a system and then the next part of combining the both and to apply it, so this is a complete and that is why we see the focus of this particular lecture is also from systems engineering point of view, introduction to neuroscience and neuro instrumentation, so it is just understanding about the basics of science but also applied of application of the science.

So, let us see quickly how the e-beam operation works and then we will take it to the magnetic sputtering, then I will give very simple example of how the EEG electrodes or a patch can be deposited it is so easy you will love it. So, let us see the slide once again, you see that in electron beam operation the practical power densities if you see the slide is around 10 kilowatt per centimeter square.

And these are utilized in melting metals but dielectric requires only 1 to 2 kilowatt so that is what is required only 1 to 2 kilowatt per centimeter square. Now, the contamination level of deposited film using e-beam evaporation is less than other PVD and that is why it is better and like I said the electron density je leaving the hot filament is due to the thermoionic emissions and is explained as you would very well know is expressed by Richardson equations which is given here.

Where you can say A is a Richardson constant and it is given by $1.2*10^{6}$ A power by m square which is ampere by M square and q is given by $1.602*10^{-19}$ coulomb and phi is the work function of the material you will know about a phi when you look at the semiconductor and metal junctions or metal-metal junctions it is a whole different area where you talk about physics of semiconductor devices, we will not go into detail about the work function other places right now, we want to know that what are the equations related to the electron beam evaporation system.

And you will see that near the evaporant surface, the evaporant flux shows the laminar flow and uniformity of thickness can be described by your cosine law. So, you will see that generally we keep the substrate at 90 degree with respect to the source material. Why it at 90 degree? Because of the cosine law the maximum deposition will occur at the, when the substrate is kept at 90 degree compared to the other places of the chamber, why not you put subset here or here, why only you put in the center and that too also at exactly 90 degree with respect to source is because of this same reason.

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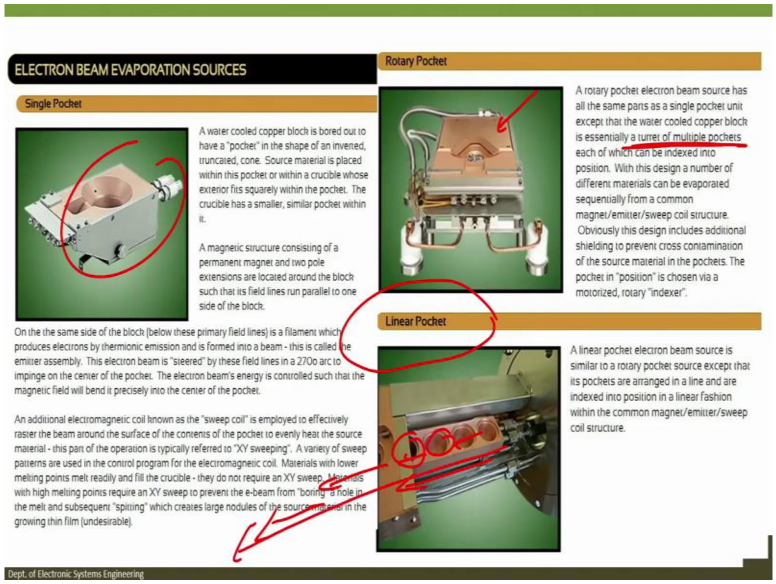

So, let me go to the next one. Now, when you talk about electron beam evaporation you should also know the electron beam sources. So, you see the first source which is shown here it is called single pocket source and a water cooled copper block is bored out to have a pocket in the shape of invented, inverted truncated cone and you can see here that it goes like this and further it goes like this that is why it looks like a cone.

Source material is placed within the pocket or within the crucible with exterior fits. A magnet structure consisting of permanent magnet and two pole extensions are located around the block such that these field lines runs parallel to one of the sides of block, you can read it further that how this electron beam is steer it is similar to the one that we discussed earlier, it is 270 degree arc to impinge on the center of pocket and the electron energy is controlled such that magnetic field will bend it precisely to the center of pocket.

Now, what is the, and then, and as we mentioned earlier an electromagnetic coil known as “sweep coil” is employed to effectively raster the beam around the contents of the pocket to event the, evenly heat the source and it is also called “XY sweeping”. So, you can have a point source, you can have XY sweeping, you can have raster scan, you can have triangular sweeping and many more.

The advantage is there is only one source material here but so that the complexity of the system will be less but the disadvantage is that you cannot deposit multiple material to do that you have two options either you go for the rotary pocket or you go for the linear pocket. Now, as the name itself says rotary that means that the, this is the one pocket that you can see there are multiple sources behind this shield. So, when you want to deposit one material, the electron beam will hit this particular material here this one and then when you are done with that then you can rotate the material so what will happen?

This guy will go here, this guy will come here and this guy will come here. So, you can rotate the sources and that is why you can deposit multiple materials in the single vacuum cycle. So, a rotary pocket electron beam source has all the same parts as single pocket, it is similar to this but it has multiple sources except the water cooled copper is essentially a turret of multiple pockets, there are multiple pockets, we with this design a number of different material can be evaporated sequentially from a common magnet emitter or sweep coil structure.

Obviously, this design includes additional shielding to prevent cross contamination, this is the additional shielding. The pocket in a position is chosen via motorized rotary indexer, you can select pocket 1, pocket 2, there is a motor which will rotate this particular pocket. The next one again you can do multiple deposition by using a linear pocket and in a linear pocket electron beam source is similar to rotary pocket except that its pockets are linear.

So, whatever you want to deposit this will move this way once you are done it, there is a space in this side also, so if this comes here, then this guy will come next to it and then you can, so it goes all the way it can go back, to this side and the last one will be focusing on the electron beam. So, this is another way of depositing the material.

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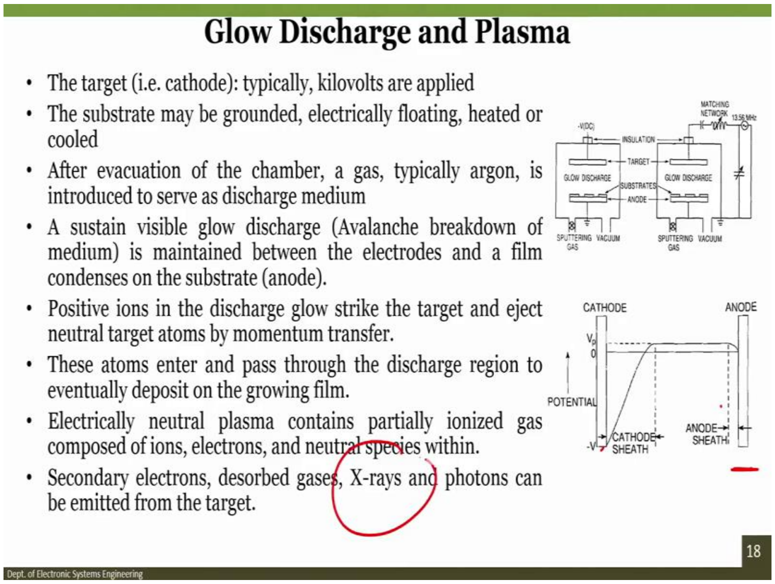

Now, when you talk about depositing you should also know that what are the glow discharge and plasma. So, the target that is cathode you see here it is easy for you to understand from this particular the schematics you see here that there is a voltage, there is a insulation target and substrates, this is the anode and this is the cathode which is your substrate is at the cathode and then you can so again for we are done with electron beam evaporation, so we are done with the electron beam evaporation.

Now, we are moving towards sputtering. Sputtering, sputter. Now, why this word sputter is there? Sputter is similar to, if you have ever noticed the rain drop falling on the metal roof, the rain drop that falls on the metal roof will form a noise similar to sputter and that is why the word call sputtering came into the this, for this particular system because here also it looks like you are dislodging the atoms from your target onto the substrate and it goes atom by atom. So, it falls like a rain drop on to the substrate so that is why the name sputter came.

Anyway, coming back to here there are different kind of sputtering, one is called DC sputtering and one is called RF sputtering. Of course DC stands for direct current, RS for radio frequency way of you generating the field and when you talk about radio frequency you already know there should be a matching network, there is a frequency generator which is at 13.56 megahertz and then there is a capacitor inductor which constitutes a matching network. Here the beauty is that the target is at the top and the substrate is at the bottom. The substrates are anode and the target is generally at the cathode region. There is a insulation film outside the chamber, so that when you touch the system you will not get any shock.

Now, how this happens? See, again it is a vacuum based deposition. So, we have to connect it to a vacuum pump so when a vacuum pump is connected the system will be evacuated, when a system is evacuated you can insert this sputtering gas, when a sputtering gas is introduced it will start heating the target material and because it starts heating the atoms from the target material will dislodge and once it dislodges it will gets, it will start depositing on to this particular substrate. So, this is how this sputtering works.

Now, when you see this you will see a glow discharge here there is some purplish color is here and how this glow discharge and plasma is formed, so that is the text that is written here target cathode typically kilovolts are applied. The substrate may be grounded, electrically floating, heated or cooled that means this particular substrate you can see, in this case it is grounded or it can be electrically cooled and it should be or it can be electrically floating.

After evacuation of the chamber the typically argon is introduced to server discharge medium assist sustained visible glow that is also called avalanche breakdown of the medium is maintained between electrodes and a film. So, in another way if you see the potential between when you apply a potential there is a cathode sheet and then there is anode sheet and here you can see a uniform avalanche breakdown medium and the positive ions in the discharge glow stick the target and eject the neutral atoms by momentum transfer which is these particular atoms are dislodged and it will come down.

These atoms enter the pass through the discharge region to eventually deposit onto the substrate and grow the film. Electrically neutral plasma contains partially ionized gas composed of ions electrons and neutral species we know that, secondary electrons or dissolved gases X-ray photons can be emitted from the target, that is a little bit difficulty that there can be generation of X-rays which we do not want in the in the case of depositing a material.

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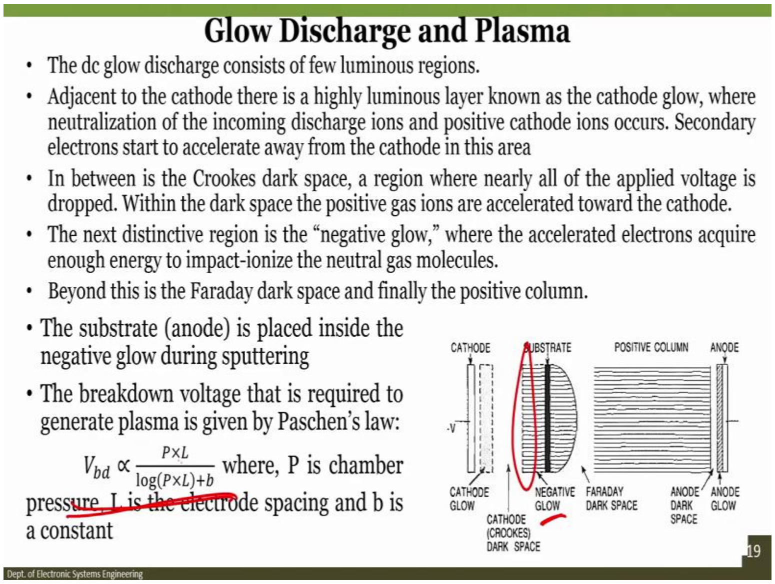

Further, if you want to still dig down into the mechanism then let us see, see this is how it actually happens, there is a cathode and then there is a anode on the other side, there will be cathode glow the substrate is generally kept at the negative glow and then there is a positive column, in between the negative glow and a positive column there will be faraday dark space and then towards the cathode side there will be negative glow and between the substrate and cathode again there is a block and again there is a dark space here it is called cathode or Crookes dark space.

So, there is a anode dark space, then there is a anode glow. So, if you come from this side towards the cathode then what you see, that there is a anode dark space then there is a anode glow, then dark space, then positive column, faraday dark space, then there is a substrate and then there is negative glow, again cathodes or Crookes are placed and finally cathode glow and cathode. So, the DC glow charge consists of a few luminous region that you can see here adjacent to the cathode there is a highly luminance layer known as the cathode glow where neutralization of the incoming discharge ions and positive cathode ions occurs.

The second electron starts to accelerate away from the cathode in this region and in between the Crookes dark space a region where nearly all the applied voltage is dropped within this dark space the positive gas ions are accelerated towards the cathode and a distinctive region is called a negative glow which is here where the accelerator electrons require enough energy to impact the neutralized gas molecules.

Now, beyond this faraday dark space and the finally the positive column the substrate is placed inside the negative glow during the sputtering mechanism and the breakdown voltage that is acquired is again given by Panchen's law which is shown here and here we can see that the P is a chamber pressure and L is the electrode spacing where b is the constant.

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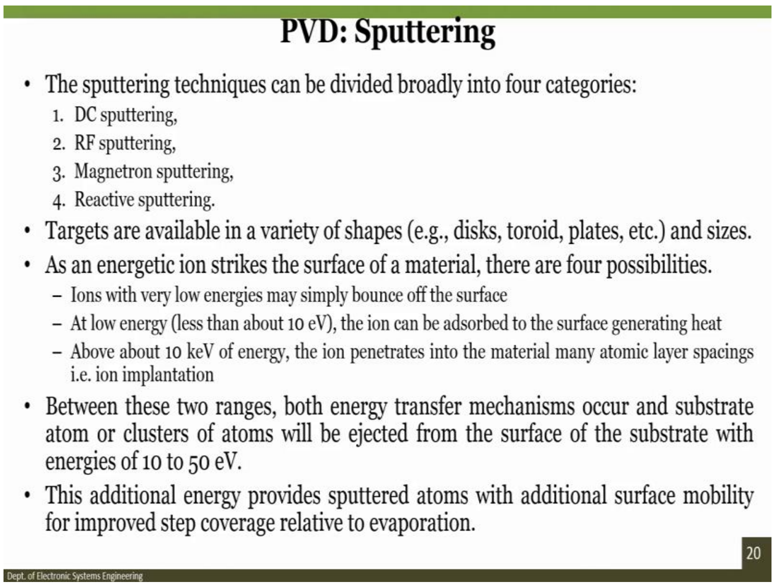

So, as we saw earlier that electron beam and thermal evaporation, thermal evaporation they consist under the evaporation kind of system or electrically driven system for depositing a film where in case of sputtering it is a mechanical way. Why mechanical way again? Because in this case you insert argon and argon will target they target molecules and atoms they are physically dislodged, when you hit what will happen is let us say you take an example of a wall and throw a stone, if the wall is made up of cement the cement particles will be dislodged, same thing but at a different level.

So, if you have a chamber and it is a high vacuum, you have a target, if you insert or let the argon, you insert argon gas and the argon gas will hit the target and will dislodge the atoms these atoms that is dislodged which fall down onto the substrate. So, mechanically dislodging the atoms from the substrate to grow a film and that is why, so when you dislodge these atoms, the atoms will drop one by one like this, tak, tak, tak, tak, tak, and that is why it is kind of sputtering, you understand?

When I was talking about a metal roof with a rain drop you will have the same sputter sound, so similar to sputtering sputter sound we got sputtering, but in sputtering again if you want to go further there are 4 types of sputtering, one is called DC sputtering, second is called RF sputtering, third if you want to add the magnet to improve the, the deposition rate and also to have the sputtering area confined then it is a magnetron sputtering and finally you have a reactive ions or reactive sputtering. So, 4 kind of sputterings are there and generally, in this case, we do not use metal chunks or a wire, here we use disk.

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So, disk is loaded on to the target, so like let us say this is a target you have to hold a complete disk instead of holding let us say this is a disc and you are holding a complete disc instead of just a chunk that is why the target is at the top generally. So, as I told you if you see the slide the sputtering techniques can be divided broadly into four categories, so till then you take care I will see you in next module, bye.