Bio - Microelectromechanical Systems

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Module No. # 01

Lecture No. # 37

Hello and welcome back to this 37th lecture on Bio - Microelectromechanical systems. Do a quick preview of what we did last time; we talked about some basics of photolithography.

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Review of previous lecture

- Basics of photolithography
- Different types of photolithography.
- How does a negative tone photoresist work?
- Deposition methods, VTE, E-beam and sputtering technique.
- Deposition and lift off.
- Doping and ion implantation.
- Microstereolithography.

We also discussed different types of photolithography, contact proximity and projection modes. Wherein depending on the requirement and the usage, you could determine whether you want to go away with an expensive optics or you want to make the optics simpler and go away with touching the mask every time to resist surface. What the conclusion was that projection systems are much more expensive, it is more difficult to create high resolution in comparison to contact mode. All the laboratories or the research work is done using contact photolithography. We also talked about how a negative tone

photoresist would typically work. It starts with its combination of an epoxy resin - a solvent, which are normally cyclopentanone and then a photoacid generator. As and when the light falls onto the photoacid, it generates an additional proton; it is a weak acid or a Lewis acid. The proton actually goes into or diffuses the epoxy resin network and opens up the epoxy chain cross bonding them to each other. So, wherever there is acid generating proton depending on the exposure of light, it almost always immediately forms and gets into the resin, cross bonds the resin. Therefore, a negative tone resist essentially cross bonds on exposure to light and stays back. The remaining portions which are unbounded still have the epoxy chain intact or can be removed by using a developer solution.

We also talked about deposition methods, wherein thin films of metal vapour could be taken onto the surface of wafers. This typically include vacuum thermal evaporation techniques, E-beam based evaporation and sputtering technique. As you know, sputtering is essentially plasma driven process, but there are two target plates, you create gas plasma comprising of ions and electrons.

Basically drive the ions towards the target, so that it up blades the material off the surface of the target and creates a metal vapour. These vapours are then transported onto the surface of a substrate, which is placed perpendicularly below and certain bias potential is applied. Therefore, there is a tendency of these metal vapours to go on a kind of high impact basis to the surface, thus sticking to the surface and staying back.

Normally, you also use some kind of an adhesion layer between the metal layer and the silicon dioxide. This adhesion layer could depend on what is being deposited at the top, like in case of gold, you use a chrome layer and in case of platinum, you use titanium. So, there are various mechanisms have been found out by x hardy, wherein you could have formulation of oxides on both sides. Thus, a kind of interweaving into the lattices of silicon dioxide on one side, on the other side that is platinum on other side, so on and so forth.

We also talk about this wonderful technique of liftoff, which is very often used in IC fabrication processes to build conduits or interconnects on the chip. Deposition followed by liftoff is essentially starts with photolithography process, wherein a pattern is opened

up in a positive tone photoresist, and vias or capillaries are realized on the shape corresponding to the shape on the mask.

Then, these vias are essentially filled with metal vapours. The photoresist, which is present in the surrounding area, is removed later on by using a solvent - organic solvent like acetone. So, it results in actually staying back of the deposited metal, which can form as conduits or interconnects and MEMS circuitry.

We also talked about doping and ion implantation essentially for microelectronic MEMS. You need to dope silicon with group 3, group 4 or group 5 material depending on whether you want to make a P-type or an N-type. Essentially, you need to implant through purification process high momentum ions onto the surface of silicon. So, the way you do it is using Lawrence forces and exploiting a magnetic field, you basically prepare a hydride gas or some kind of a gaseous state of the particular species that you want to implant. Then, you ionize this gas and accelerate the ions - the metal ions like boron or arsenic or gallium through long tubes and perforated cathodes respectively.

The idea is the acceleration goes on building up and then there is a central magnetic field, which is applied to divert these ions and separate them on the basis of their mass. They would all move at different accelerations depending on - if the field is constant depending on their charge per unit mass ratio. If you assume the charge is to be same, the mass is typically varying would mean different degrees of acceleration.

Therefore, the velocity and magnetic field zone would be all different; they would be reflected with different angles in different directions. You can actually purify and filter off a particular species over others, then use that to impart momentum onto the surface of a silicon wafer. In the process, kind of escapes into the lattice, the lattice opens ups and gives way to the particular material, it goes on as a void into and part becomes a part of the crystal. So, thus having a common conduction band with the other areas of the crystal, thus the excess electron or an excess hole or vacancy is creating a P-type or an N-type wafer.

We talked briefly or touched upon briefly into this wonderful three dimensional lithography process called microstereolithography, which is also borrowed from rapid prototyping technique. Wherein any geometric model is split into different layers, these

layers are essentially built by lithography using a negative tone photoresist. Every time there is a spool, which comes up in different steps in shot micrometer size steps. If super focus a beam at different levels, so that you can put together a cross bond the resist. So, you can build the whole structure out of different cross sectional areas available for as a post microstereolithography.

So, I also refer to the DMD based or the LCD projector based microstereolithography systems, wherein the whole image can be translated onto a wafer using a set of Texas Instruments, digital micro-mirror devices, which turn off and on, and creates a pixel or turns off a pixel. Therefore, you can realize the whole image using such pixels and can develop the optics around, so that this can be translated directly onto the surface of the resist.

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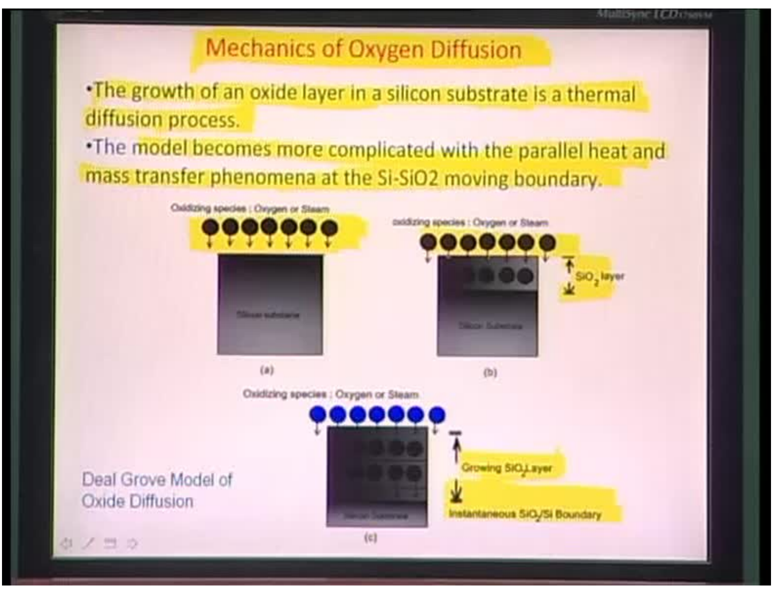

Having said that we would like to go into a little more of fabrication steps, we were talking about oxygen diffusion, we were talking about wet and dry oxides, formulation of wet and dry oxides. Essentially, if you look at, today, I would like to discuss this process of mechanics of oxygen diffusion.

As you know, the way that oxides are grown typically onto silicon wafers are thermally done, wherein the wafer is heated to about 800 to 1000 degree Celsius. Then, it is exposed to either dry oxygen or weight oxygen, thus there is a diffusion mechanism,

wherein oxygen ion goes into the vibrating lattice, gets to be a part of the lattice and slowly eventually develops into silicon dioxide.

Essentially, oxidation is a process, wherein at the expense of silicon you are creating silicon dioxide by diffusing oxygen at a high temperature. What typically happens is that the surface atoms start vibrating, the lattice starts vibrating at a higher temperature. There is a lot of kinetic energy as the oxygen is slowly comes to the surface, it is taken up by the vibrating lattice systems, these atoms can go into and create oxides from a certain depth onwards. Now, this being a diffusion driven process, it is also controlled in terms of its rate of growth with the active concentration that is available onto the surface. There are a lot of models, like one of them is Deal Grove model, which talks in details about the diffusion kinetics.

Here, what happens is that the growth of an oxide layer and silicon substrate is a thermal diffusion process. The model becomes more complicated with parallel heat and mass transfer phenomena as the Si-SiO2 boundary moves more into the surface. You can see here that the oxidizing species are coming from the oxygen of the steam, they enter into the Si layer and thus SiO2 is formulated. Essentially, this layer grows with time, but the rate of growth decreases with time as well, because you have already a higher concentration of oxygen, so lower gradient effectively with the atmosphere. Therefore, diffusion is also rate limited in that case.

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Polymer MEMS

- Polymer MEMS is application of polymers to build micro features and structures.
- Polymer MEMS become prominent as we operate at the interface of life-sciences.
- This is owing to the friendly nature of the organic surfaces and interfaces to biological entities.

We would now like to talk a little bit about polymer MEMS. Essentially, polymer is the area especially in biomems to go by or to take off, because of the fact that the biological entities are not very happy about inorganic environments. They prefer materials which are carbon rich. One of the reasons why carbon MEMS has become popular is because, the behavior of biological entities in the presence of carbon is or carbon rich substances is really the usual behavior and there are no toxic effects whatsoever in such environments.

Polymer MEMS is then defined as an application of polymers to build micro features and structures. As you know, polymers become prominent as we operate to interface mostly with life sciences, particularly owing to the friendly nature of organic surfaces to biological entities.

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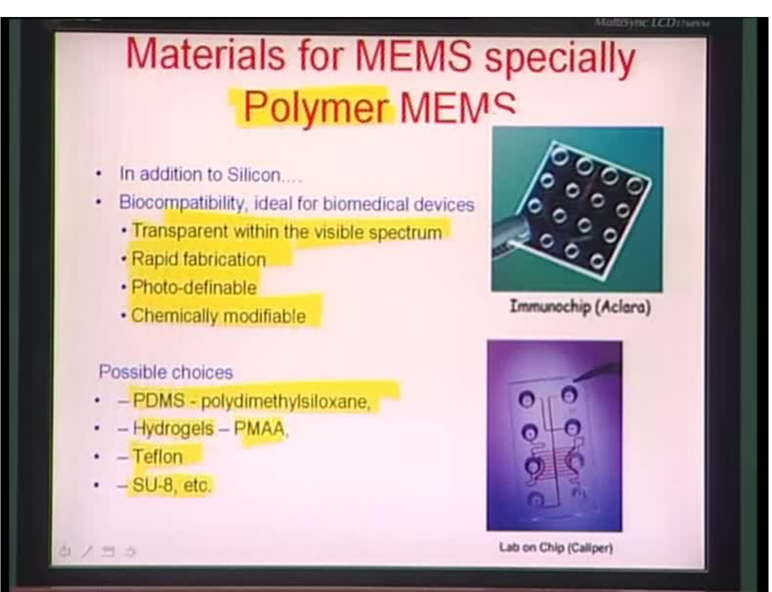

Some of the materials that are used are often are silicone rubber like polydimethylsiloxane, hydrogels poly methyl methacrylate, which is also an E-beam resist. Teflon which is a very highly hydrophobic material, SU-8 which is again a photoresist, this is essentially a negative tone photoresist, which cross bounds on exposure to light.

Some of the criteria's which are used for selection of materials, particularly polymer materials for biomems applications, are transparency within the visible spectrum. We

know that biomems devices typically have lot of transduction ways and means, wherein the active signal which is chemical, probably most of the cases is converted into optical readouts. So, you need transparent covers or the material which holds these should be transparent for to atleast the visible spectrum, to gauge the fluorescence intensity properly and express that at a function of whatever concentrations of the species are changing within the particular housing.

They are also selected based on how rapidly the features and structures, especially micro features and structures can be fabricated on them. It is preferable that these polymers which come for biomems are photo definable in nature; you could actually use light to define their features. Then, you should have chemically friendly surface, which is modifiable with different means, because essentially this is the way to go for attaching selective species like antibodies or other moieties - biological moieties like DNA, etcetera onto the surface.

Some of the illustrations which are shown here, this for instance is an immunochip from clara technologies, this is a lab on a chip from the caliper technologies; they are both commercially available prototype systems. They are made using several different techniques, let us actually discuss in detail some of these techniques available for particularly polymer MEMS.

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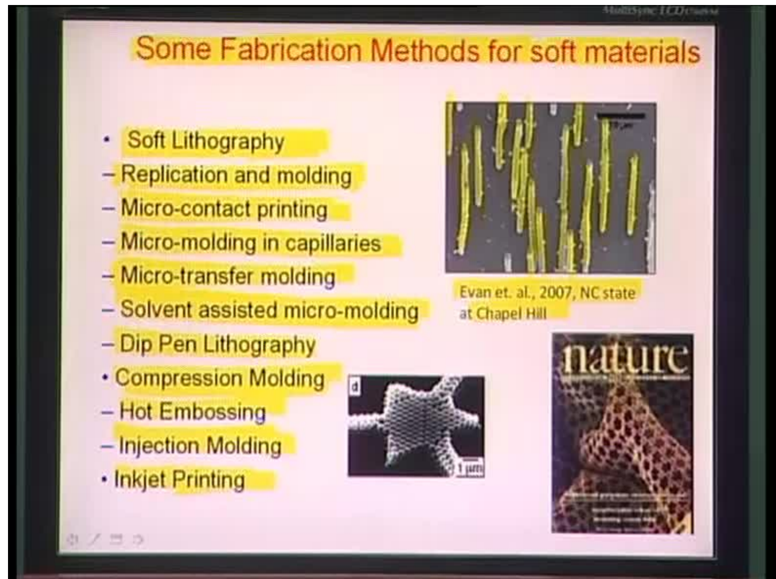

Really this area is also known as soft lithography, because of the metals or the materials that are used are soft in nature - the polymers are soft in nature. This started with a group - the white sides group at Harvard, essentially he reported for the first time this silicone based polymer, which could be used for the process of replication and molding.

If you consider this soft lithography, it is divided into several different approaches. This for instance is replication and molding, you have micro contact printing, micro molding in capillaries, micro transfer molding, solvent assisted micro-molding, dip in lithography so on, so forth. You also have systems related to compression molding, which is actually the conventional complacent molding and we will actually discuss these details in next few slides. This includes hot embossing injection molding and then the other typical method is inkjet printing.

Some illustrations here are very wonderfully shown. This is a paper reported by Evan et.al 2007, wherein he builds these high aspect ratio features and structures as you see. This close to about 30, 40 microns in height, only about 2 microns in diameter or so (Refer Slide Time: 14:40).

This kind of a high aspect ratio structure is only formulated by putting in additive to the soft polymer – polydimethylsiloxane and then actually using some kind of a mold to actually make these cilia here - likes moieties. The idea here was that the filler here was actually magnetic, it was Fe2O3 based or some other material based, which would actually be used for tentacles. When you actually rotate the magnetic field around it, the cilia would start rotating, it would create some propulsion. That is typically how bacteria do swim by using their tentacles inside solutions. So, it was a kind of mimicry of a naturally available system.

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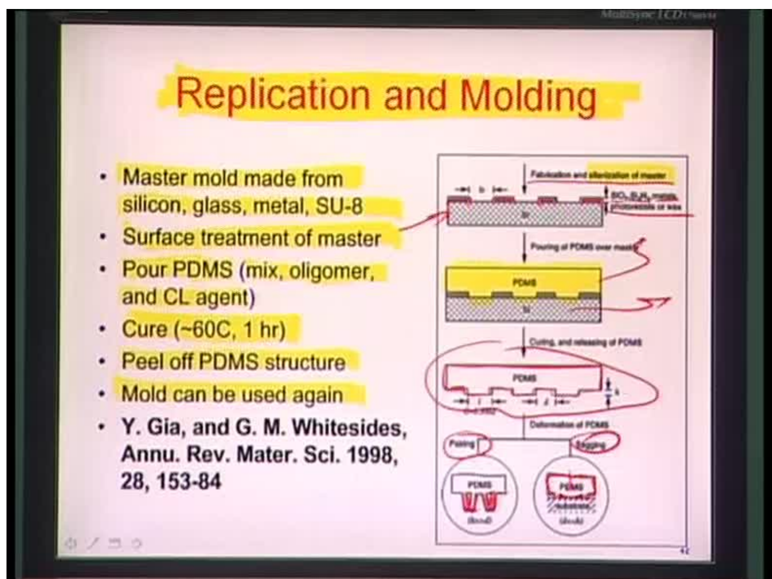

Let us talk a little more details about these independent techniques. Let us start with replication and molding. Essentially, in this technique, you need to develop some kind of a mold as you are seeing here in this illustration. This mold can be made in a hard material, could be made up of silicon dioxide, silicon nitride, metals, photoresists or wax. As you see here, this surface is essentially photo patterned and material is pretty hard. Therefore, this can be created by any etching means, whether dry or wet or laser based physical or chemical so on, so forth (Refer Slide Time: 15:55).

Once this pattern is modified or this pattern is realized on the surface of this particular wafer, you need to actually go ahead and clean the pattern, also make the surface chemically inert. So that once you pour materials around it to mold, the mold should be able to independently get released from the cast. Essentially, you use something called mold release agent or silenize the surface.

You are making the surface hydrophobic, so that it repels the polymer, which is put on that. After this mold preparation process is over, you use poly dimethyl siloxane, which is essentially a mixture of an oligomer and a cross linker agent or a curing agent, certain ratio by weight. The idea is, this is a compound, which is liquid at room temperature, but if you mix or stir the curing agent well, heat cure it, develops cross bonds, it is like a growing epoxy chain. So, it becomes hardened and rubbery when such a heat treatment is carried out of the particular solution.

What you do here is you pour the PDMS from the topside, as if it has been casted over the mold which you created in the previous step. Then, you essentially heat cure the PDMS. The idea is the mold can now be taken off after this is cured, this can be separated like the negative PDMS piece of the mold. So, whatever is there on the mold surface is actually transferred onto the PDMS; the negative of that is transferred onto the PDMS surface.

Now, you can use these shapes and features as channels, chambers, so on and so forth. You can actually bond two pieces of these PDMS, replicate it together or you can bond this with another piece of glass, where you could position that with different electrodes etcetera. The idea is that you could build up micro system devices based on this technology. One more issue here is the aspect ratio, which needs to be carefully precisely done while designing. As you know, PDMS itself being a soft material, there is always a tendency of these kinds of extra arms or long arms to pair up or sag down as you can see here, so the aspect ratio of design is very critical.

The sagging down would happen to overweight, is particularly when the posts to support the whole structure are very small, they are spaced by a large distance, whereas this adhesion mechanism between the two projected pieces would work out, when the material is too long in comparison to the distance of separation. They are like filaments coming out; they are tending to adhesion between each other by local van der waals forces of attraction interaction.

In a nutshell; in this replication process, you start with master mold made from silicon glass metal, is SU-8. Your surface treat the master pour PDMS, which is a mix of oligomers and cross linking agent. Cure this for about sixty degree Celsius for 1 hour, peel off the PDMS structure again and then the mold can again be used in the process; that is what replication molding is.

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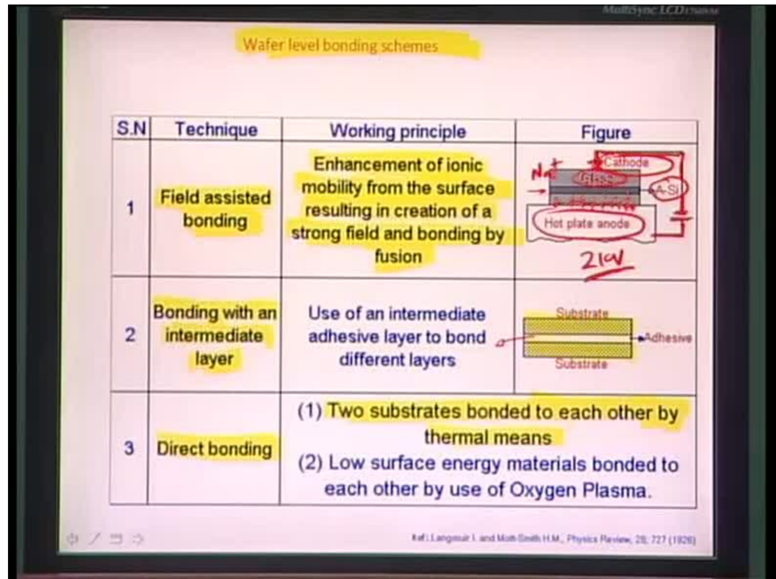

Wafer level bonding schemes

S.N	Technique	Working principle	Figure
1	Field assisted bonding	Enhancement of ionic mobility from the surface resulting in creation of a strong field and bonding by fusion	Cathode Glass A-Si Hot plate anode
2	Bonding with an intermediate layer	Use of an intermediate adhesive layer to bond different layers	Substrate Adhesive Substrate
3	Direct bonding	(1) Two substrates bonded to each other by thermal means (2) Low surface energy materials bonded to each other by use of Oxygen Plasma.	

Let us look at the some of the other schemes, which can be used once the replicated piece is available for creating channels and chambers which are enclosed. The best way to do it is to bond two pieces back-to-back, wherein you have a piece on the replicated site and another glass piece on the bottom side. You basically change the surface energy of both these by using gas plasmas. Let us look at the different type of bonding schemes which are available for MEMS in general, then we will translate back to polymer MEMS and try to focus more on to the gas plasma-based surface energy modification causing bonding.

If you look at different schemes of MEMS, wherein inter wafer bonding can be realized between different levels of the same wafer. The first technique that is used is field assisted bonding; here, essentially there is an enhancement of ionic mobility from the surface resulting in creation of a strong field and bonding by fusion between the two plates between the two participating wafers.

Essentially, what it means is that for example, if you want to do bonding between soda lime glass, as you can see here, with number of sodium ions and silicon - this is a small layer of amorphous silicon as you can see. Essentially, you use or deposit this amorphous silicon layer on the top of another glass, as you can see here bonding is really between the glass and the amorphous silicon (Refer Slide Time: 21:24).

What you do essentially is, you make this connected to a cathode. So, this is a pointed cathode with a certain pressure, it is connected to a high voltage source which can give voltages up to about 2 kv or so. Essentially, this end is connected to the hot plate, which can go up to temperatures as high as about 200 to 250 degree Celsius. What it is used to do is to give a positive potential to this particular plate.

You already have an anodic site as the hot plate, so what you think will happen? The soda lime glass having Na plus ions; the Na plus would go away from the interface. Similarly, the O minus groups on the top of silicon dioxide would try to actually go towards the anode and it creates a depletion region. This depletion region is a no charge region, it is somewhere in the center, because of this sudden depletion region is created there is no intercommunication between or there is no charge based repulsion or attraction between the lattices. You can create thermal bonding between the two lattices by applying pressure and heat simultaneously; this is known as anodic bonding. Because, you are essentially creating a charge depletion region for bringing the lattice structures closer to each other. So, that they can formulate interlaces and lattice bonds between the different levels of the wafer.

Having said that another bonding principle - wafer bonding principle is bonding with an intermediate layer, as you can see in this particular illustration here (Refer Slide Time: 23:29). Here, what you are doing is, you have two substrates, which you would like to bond to each other using an adhesive, which comes in between here. So, this is like more gluing the two substrates together. Now, you can spin core, the glue onto one substrate or to other, or you could just apply it using any other process like just brush coding maybe, then you press the two substrates together out until they bond.

However, this is not a very good technique in MEMS, because the MEMS features are very small in nature. The adhesive layer that you use is sufficiently thick to cover the features, create problems related to the structures and the aspect ratios within the surface of the wafer.

Other scheme which is used is direct bonding, wherein the two substrates are bonded to each other by thermal means. Essentially, it just means, you take two glasses or you take silicon and a glass, and then keep it under pressure and temperature. So that the lattice gets bonded to each other at different places, at a sufficiently high temperature, let us say

about 400 to 500 degree Celsius. The other means of direct bonding, which is very commonly used particularly in polymer devices, is by changing the surface energy of the materials by using oxygen plasma.

Here, materials which are treated to oxygen plasma generate a low surface energy. Normally, having a lower surface energy generate a high surface energy on treatment with plasma, in other words, it becomes a highly hydrophilic from hydrophobic nature of the polymer after the plasma treatment is carried out on their surface. Such two surfaces can very well react to each other; especially if there is a silox and backbone, in one of the polymers develop a SiO Si Silenole kind of linkage between the two participating layers.

It also releases a water molecule in the process of developing this particular bond, has been illustrated by people earlier in different research work. This is a very wonderful technique, a clean bonding process, wherein without any intervention or with very minimal intervention you are able to bond materials to gather just on the basis of change in surface energy of different surfaces.

Let us now delve a little bit more into this whole mechanism of gas plasmas and as to how these plasmas are really formulated, how it can behave to create different impacts on the surfaces. This essentially is borrowed from topics of plasma physics, but it is very important and critical to understand these basics for understanding the other fabrication techniques and processes, which are normally available like dry ion milling so on and so forth.

What is plasma? Plasma is a system of electrical neutrality, which composes of positive and negative charged elements. Overall the whole medium’s charge is neutral, being because of the principle of electro neutrality which exists in nature, but then there are separated ion centers, the positive ions are separated and then the electrons which are around.

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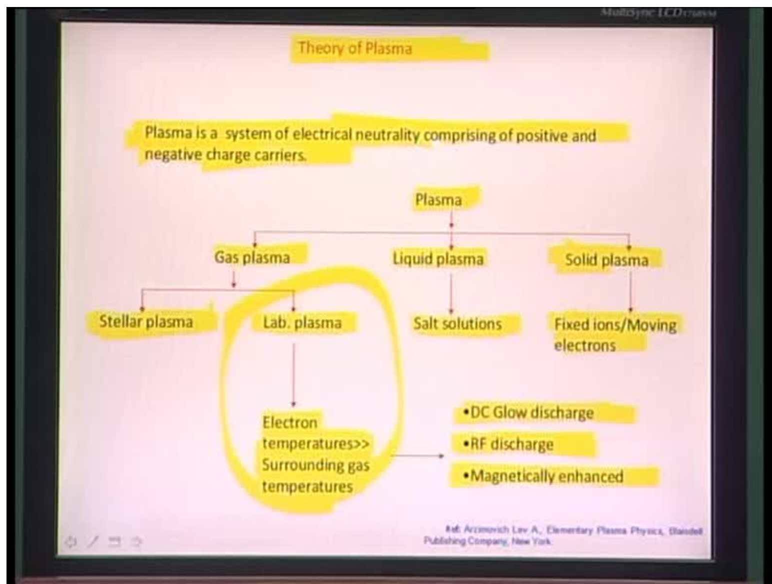

Typically, plasmas are can be divided into gas state plasmas, liquid plasmas and solid plasmas. Gas plasmas again are basically comprised of gas molecules, which formulate into gaseous ions and electrons. These can be classified again into stellar plasmas and laboratory plasmas based on what is the state of its electron temperature in comparison to the surrounding gases.

Now, in stellar plasmas, typically which is found all through the space, this plasma is created just because of thermionic effects, where due to superheating of gases confined to a certain feature gravitationally in space. There is almost - always a tendency of materials to give out electrons, and generate ions and electron pairs. Here, the electron temperature is much higher than the surrounding gas temperature, because you have already given it enough kinetic energy with by thermal means.

In laboratories plasma, however the same electron is taken out of the materials by some alternate means, like electric fields or using some other properties, which I am going to cover in just about few slides from now. Here, the electron temperature is normally much higher than the surrounding gas temperatures.

Stellar plasma, thermionic effects surrounding gas temperature is higher than electron temperature. Laboratory plasma made with other alternate mechanisms of ionization,

surrounding gas temperature is cold and the electron temperature is really very high. We sometimes call such plasma systems as cold plasma systems.

Liquid plasma again, plasma in liquid form, salt solutions are wonderful example. Blood itself is plasma containing ions, which are moving or charged species like nucleic acids or proteins which move throughout our body. Therefore, the liquid material with these different kinds of charged centers move around is also a kind of plasma.

Solid plasmas are illustrations, where you have ions which are fixed and electrons which are hopping or moving between the ions, as happens in case of a P type or an N type semiconductor. So that is typically solid plasma. If you look at laboratory plasmas, this would be our area of interest really in for a focus of study here. They are actually divided into a DC glow discharge, an RF or a radio frequency discharge and magnetically enhanced plasma. These are some of the typical characterizations into which you can fall all the different plasma. This characterization is really based on the ways and means of making or realizing the gas plasma within the environment.

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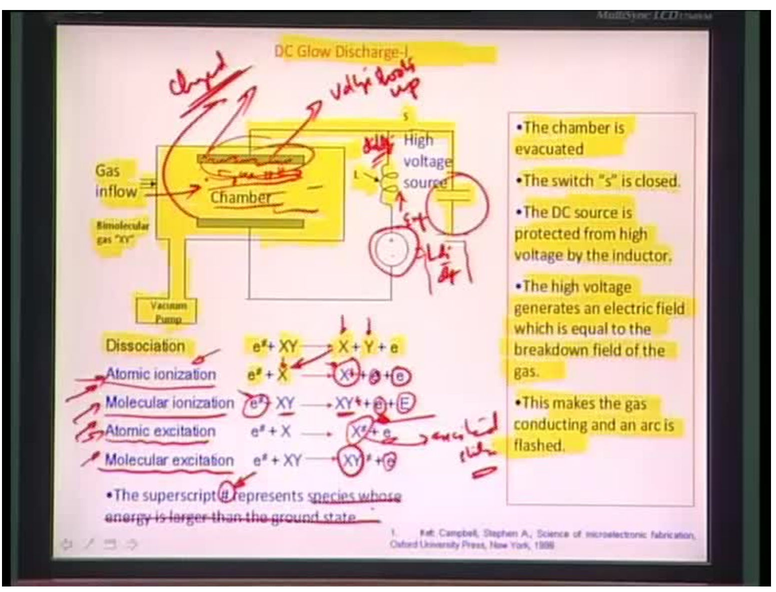

DC glow discharge – here, as you see, in this particular case, you have a big chamber, which is formulated and connected to a vacuum system. There is in gas inflow from one side, it goes out continuously, so there is an ambient atmosphere which is created within this plasma chamber.

What is also important here to mention is that these plates which are kept or charged plates like capacitors, you have a dielectric gas phase in between these two different plates. Now, the following operation is carried out. The chamber is first evacuated, a certain gas, let us say a diatomic gas xy, bimolecular gas xy as in this case is flown slowly into the chamber at certain vacuum level. The switch s here, as you can see in this particular circuit, is closed suddenly. So, there is a high voltage source, which the switch connects to the main plate here. Therefore, connecting the switch suddenly would mean the voltage of this particular plate goes or shoots up; so the voltage shoots up.

We have to protect the remaining part of the circuitry, so thus we use an inductor here, as you know, from first principles that the VF, the EMF, which is generated across an inductor, is also Ldi by dt in the reverse direction. If you have a huge current buildup di by dt here owing to the sudden connection of this high voltage source with this particular plate, the inductor would have an impedance across it, which is also equal to, so this is the impedance Ldi by dt.

You have a case of reverse EMF, which can protect this particular voltage source here, which would be used later along the line. What happens though is that because this plate is suddenly shot up to a certain voltage, it can cause ionization within the gas molecules which are surrounding this particular plate. This is really something where you have to see what is the breakdown potential of a certain medium. This is also the same way as a spark or an arc is created typically. So, you shoot up the charge buildup of a certain plate or a point to a level, where the medium within it suddenly develops a leaky mode. There is a flow of current from one plate to another through a column of ions and electrons, which are realized because of electrical breaking down of the medium.

The DC source is of course protected from the high voltage as I talked about earlier. By the inductance and the reverse effect as the current suddenly changes in the circuitry, but the high voltage that has been used to tailor or actuate this particular plate generates an electric field, which is equal to the breakdown field of the particular gas. This makes the gas conducting and an arc is immediately flashed. Let us see what happens because of this arc.

There are several kinds of mechanisms which are going on. Let us say we have a high energy electron, which has come out of the arc. The first mechanism that can happen is

dissociation, where this bimolecular gas x y is split up into individually x's and y's. These are free states, so there is no shared electron, there is always an incomplete valency in this, does not exist normally in nature. So, it is like a free radical and you have an electron which comes out.

Further, the species x can be hit by another electron; the x has been created as you know in this particular illustration here. So, this x can convert into x plus, it can generate two electrons as you can see also an electron, so this is called atomic ionization. Dissociation of the atomic gases is split into two independent components. Atomic ionization where one of these independent components is again hit with an electron, it generates a charge and some extra electrons.

Molecular ionization, where you have this x y being bombarded by e tilde, as you can see here, the high energy electron, it converts without dissociating the molecule into an ionic state. So, it is xy plus, you give an electron and some energy in this case. You can have an atomic excitation; there is a little different than atomic ionization here.

So, what happens is that the electron has energy. We can assume that if this electron is able to hit an electron in the inner orbitals of the material to go out into the outer orbital of the particular atom, so this is actually an evanescent state, it does not last for a long time; it is very ephemeral in nature. But then, when the electron comes back, it would liberate the energy in form of a radiation, but then it is also true that as the electron is in the higher orbital level, it has a disbalance and there is a certain amount of energy associated with the system.

You have this high energy states called free radicals again, where the energy is associated with a presence of a high energy electron from its normal state into a higher orbital, of course the electron is generated here. You can have a similar kind of species, we call this excited state. We can have a similar kind of excited species for the whole molecule, where the molecule, whatever electrons it is sharing and building up a molecular orbital, has this tendency of these electrons going into a higher level orbital, because of its higher energy and staying there for longer time and electrons.

In effectively, these are all the different states which can be generated by means of the plasma process or the plasma exposure process. The subscript tilde here represents

species whose energy is larger than the ground state normally. Now, let us look at what we can do once these different states are created, what we can really do this ion, electron, high energy states and free radical system that we are left with.

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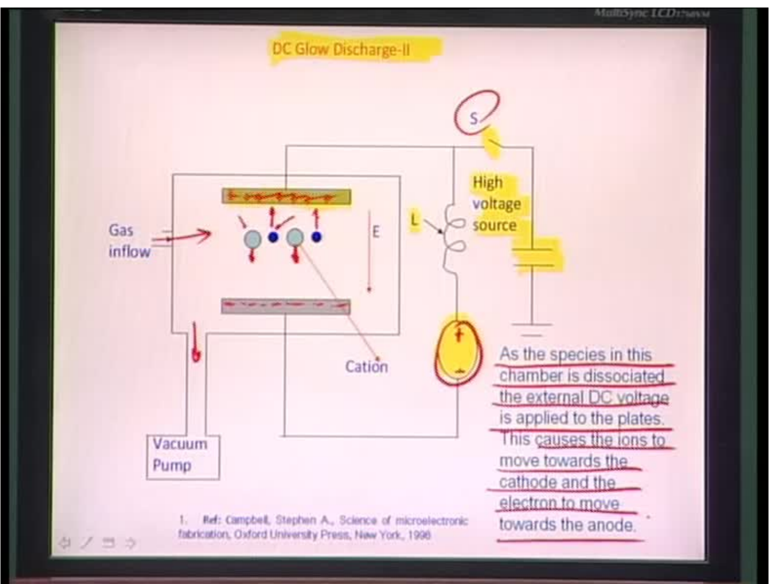

One thing that we can almost immediately do is to apply a potential - a separate potential across this particular plate. Let us suppose, you have - now in the second instance, once this plasma has been generated, switched off the switch s, what happens in this particular case is that when once this excited states of ions, electrons, high energy species and free radicals are created, you basically switch off the switch s here and disconnect this plate to all the high voltage source that it was connected to initially or previously.

Simultaneously, the Ldi by dt being smaller now, the voltage through this source voltage would be affected onto the plates. So, it effectively gives a bias to the plate, the manner that you have a positive bias given to this plate, as you can see here, a negative bias given to this particular plate from the way that this voltage source is connected to this twin plate combination.

Now, in this kind of a situation, you are having equilibrium between the gas flow and the gas outflow. You are having a formulation of ions and electrons as you can see, then you have actually decided to give it a potential or a bias over the plates.

Almost, always, what will happen is that the electrons will go towards the anode or the positive plate or in this case, as you can see, they are going in the upward direction. The ions or the heavier ions would tend to move in the downward direction, try to go and bombard towards the cathode or the negative plate as you can see here, in this particular illustration.

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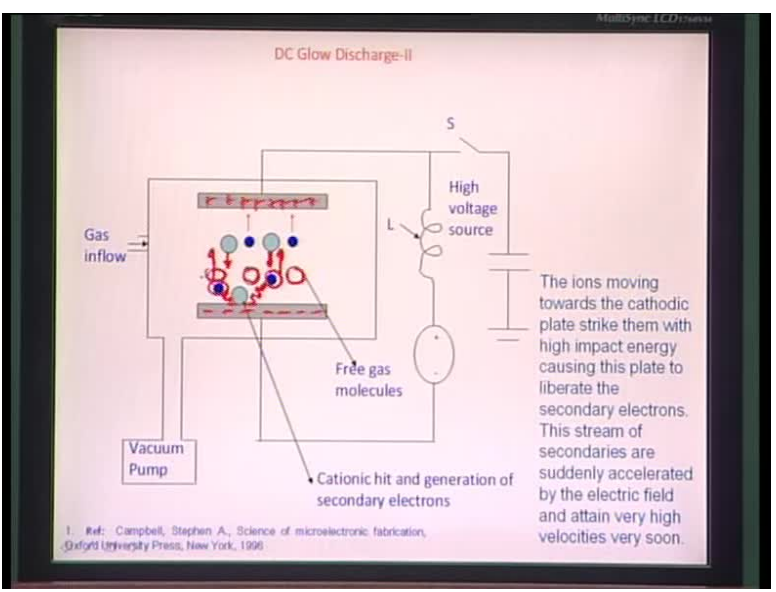

As the species in this chamber is dissociated, the external DC voltage is applied to the plates. This causes the ions to move towards the cathode and the electron to move towards the anode. Now, once this happens, this is actually a blessing in disguise, because what will happen, though if the ions moving at a high momentum would strike the cathode. They would always generate additional electrons, because of photoelectric, because of the thermionic effects.

Therefore, the ionic moment which is actually passed on all the way up to this charged up cathodic plate would result in generation of these secondary electrons. As you can see, these two blue electrons generated by this curvy path from this particular illustration, these are secondary electrons which are generated almost immediately, because of the striking of this heavier atom on the negative plate or the cathodic plate.

Once these secondaries are generated, they would also start rushing back and this rushing back would be more towards the anode, because this plate is positively charged. In the

process, they would actually create further ions by just striking, because they have some energy and they will create - this is a continuous ionization process. Therefore, once you have initiated a plasma - the plasma kind of self sustains itself, by creating of these secondary electrons and then additional ions which are generated from species, which are just about very near to the plate and which get hit to the electrons once the electron is used for bombarding the particular ion species.

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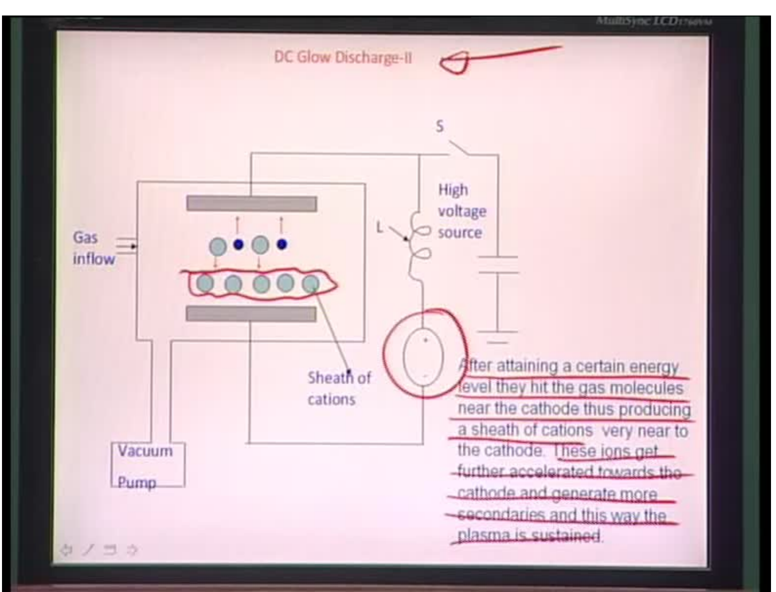

Essentially, in a nutshell, you can say that the ions moving towards the cathodic plates strike then with high impact energy, causing the plate to liberate the secondary electrons, the stream of secondary's are suddenly accelerated by the electric field and attain very high velocities very soon and thus cause fresh ions. So, there is actually a certain sheath of cations as you can see here, which is formulated - positive cations which is formulated and it is a self-sustaining process. These cations would go and strikes the plate generate, again electrons which will rush back towards the anode, create more ions. This is a recycling process, which keeps on happening until and unless the energy source is switched off. The energy source here, which is actually the energy of bias, is giving the whole energy into this system.

Therefore, whatever energy is coming here is from this bias voltage or the bias voltage source. So, this electrical energy is converted in terms of this continuous plasma formulation generation process.

In a nutshell, after attaining a certain energy level, they hit the gas molecules, these particular electrons which are rushing towards the cathode. Very near the cathode, they produce a sheath of cations, these ions get further accelerated towards the cathode and generate more secondaries and this way the plasma is self-sustaining. So that is how a DC glow discharge would typically work.

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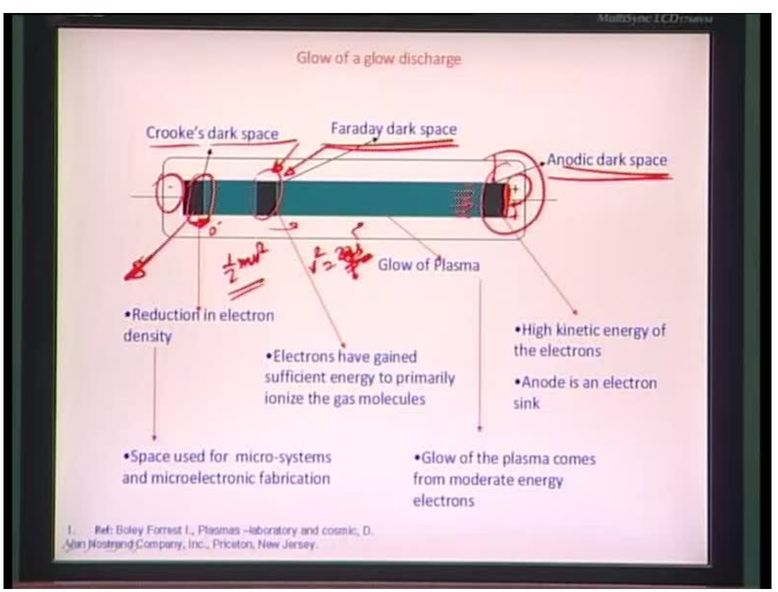

There are some interesting factors here to be considered. One factor is that if you look at what you call a vacuum tube, you have an anode and a cathode as you can see here and plasma which is generated throughout. You find out that there are dark spaces within the plasma, very near the cathode, very near the anode and somewhere in between here. This varies - the position of this varies in the effective electric field, the length of the particular vacuum tube, the kind of gas that you are using so on so forth. It is interesting to know, why or how there would be zones, where there is no light as opposed to zones, where there is light actually.

Let us consider, what is the real reason for light to come out or glow to come out of the plasma system? So, I have been talking to you about the atomic excitation or the molecular excitation, where excited states of the species are created. What essentially excited states are is that an inner orbital electron has been somehow been able to get on a higher energy level, because of the energy which is coupled to the system externally. Due to which, this electron is a high energy electron at high orbital, but really it wants to

radiate the energy out. It is not fit to be in that place, because the equilibrium of the atom has been lost, because of this the atom would definitely want to get back into the equilibrium; the system would try to get back to the equilibrium.

How it equilibrate? The electron jumps back to the lower orbital, it releases energy which is equal to - also the difference between these two energy levels and that divided by h would be the frequency of the radiation that you get and that is the glow of the plasma. That is what you are able to see as if the light is getting generated or the glow is getting generated.

What happens near the cathodic plate here or the negative plate here? There is a formulation of a dark space, which was first identified by doctor Crooke's and it is also known as the Crooke's dark space. Essentially, what happened here is that as you know the electrons which are rushing back towards the anode, especially the secondary electrons are generated by the ionic impact; it would almost always create fresh pair of irons and electrons as they move in. Their energy essentially is consumed in creating a fresh pair of ions and not the atomically excited states. The material that is created is basically losing a whole electron, rather than retaining a high energy electron.

Therefore, there is a dearth of materials, which would be actually giving glow in this particular region. There are no moderate energy states; the sheath is completely made up of ions, it is completely deionized, sorry ionized, because of the electron energy which is pretty high to dislodge an electron of an atom, rather than taking it to a higher state within the same atomic system. Therefore, you formulate a dark space in this region- this cathodic region, called the Crooke's dark space.

Towards the anode here, you form another dark space called the anodic dark space and this essentially happens because, the ions which are moving towards the positive plate generally, sorry the electrons which are moving more towards the positive plate, are generally depleted in the anodic plate, because of the high positive charge.

Therefore, whatever electrons come in this region, which would be able to generate these moderate energy atomic species, is almost always absorbed in this atomic plate here, thus creating a situation, where there are no high energy electrons to cause moderate species to come in.

Therefore, these two spaces are very clear that what happens near the anode and cathode, but there is also another region here, which is known as the faraday dark space, which is somewhere in between, which develops the same kind of modality and there are very less moderate energy species in this particular area. One of the reasons that can be explained as that the electron starts operating from here create the sheath, still some electrons escape, this electron tries to build up the energy slowly as it moves forward.

It is kinetic energy - half m v squared would be more and more with distance, because v square is assuming an initial velocity of zero is also two times a times s. a is the acceleration of the electron, s is the distance travelled. So, the distance travels the velocity square increases, probably somewhere here, the energy which is created is sufficient to ionize all the material rather than creating moderate excited states. Therefore, at that particular zone, you do not have any species which can create a moderate state. So, there is a thin layer which is created in that species, which is known as faraday dark space. It is all about how you create these excited states around the length of the plasma from the anode side to the cathode side, which would give these differences.

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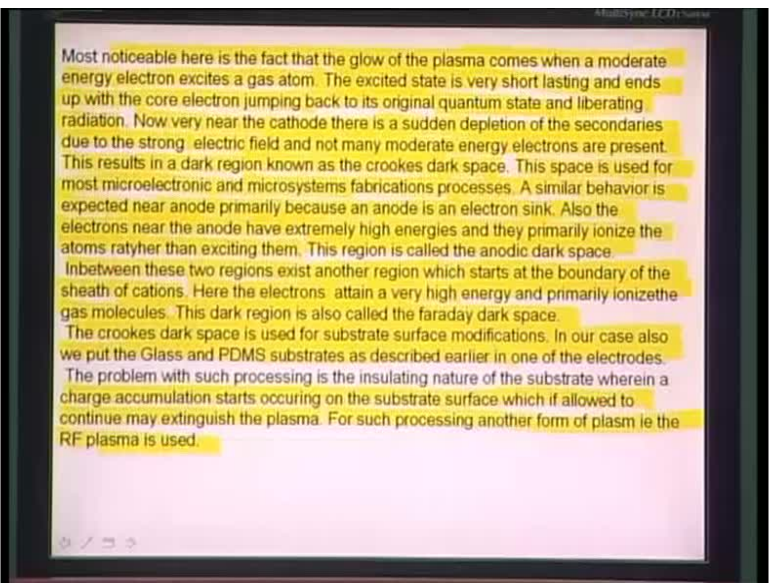

In a nutshell, we can summarize this by saying that most noticeable here is the fact that the glow of the plasma comes when a moderator energy electron excites a gas atom. The excited state is very short lasting, ends up with the core electron jumping back to its

original quantum state and liberating radiation. Now, very near the cathode, there is a sudden depletion of the secondaries due to the strong electric field, not many moderate energy electrons are present really. This results in a dark space known as Crooke's dark space. The space is used for the most microelectronic and microsystems fabrication processes, as I am going to illustrate in just about the following slides.

A similar behavior is observed or expected near the anode primarily, because anode is an electron sink, it would be able to capture most of the electrons at a higher or a positive potential. Also the electron near the anode have extremely high energies, they would rather primary ionize the atoms than exciting them into their moderate states. So, this is also known as the anodic dark space. In between these two regions, except you know, effectively there exists another region which starts at the boundary of the sheath of cations. Here, the electron attains a high energy and primarily ionizes the gas molecules; this dark region is called the faraday dark space.

The Crooke's dark space really is the space which is used for most of these fabrication processes is, like for example glass PDMS bonding is carried on using this particular Crooke's dark space in the plasma and is used for substrate surface modification. In our case also, particularly as because we are studying glass PDMS or PDMS clean bonding protocols, we use or utilize this Crooke's dark space for most of our bonding strategies or techniques.

What is one of the immediate problems which come up, because we are talking about insulating materials, there is an accumulation of charge on the surface as we put it in the Crooke's dark space. There is no way that we are raining off the charge of the surface rather the charges are getting accumulated within the material. Therefore, after a while, if more charge is allowed to accumulate within such substrate, the plasma may self-extinguish. Because, there are not enough electrons to sustain this continuous formulation of sheath process, because most of the area of the electrode is covered with such insulating materials, where the electrons if once gone in is simply absorbed, the substrate gets charged up rather than generating secondary electrons, as is normally the case in metal cathodes present in the plasma systems.

We normally have to use a different strategy for creating and sustaining the plasma for a longer time, especially for insulating substrates. Therefore, we use another strategy called RF plasma or radiofrequency plasma for this particular purpose.

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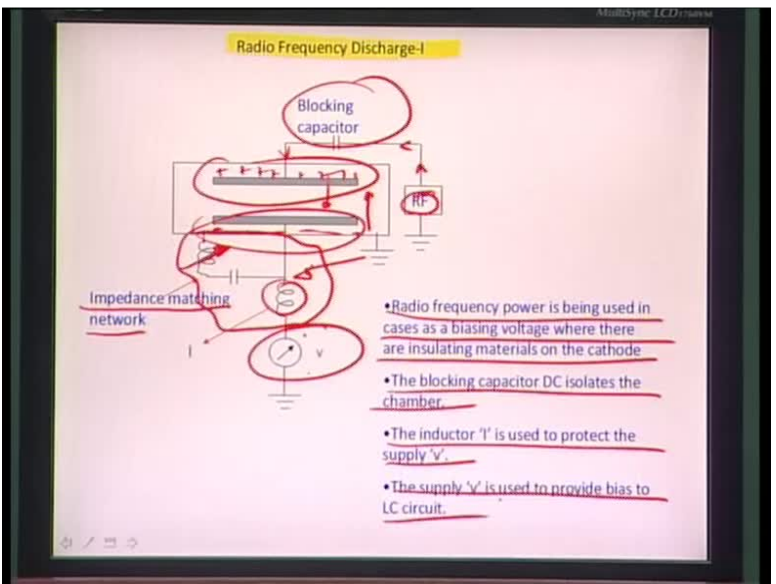

Let us see, what RF plasma really does. The RF discharge of the radiofrequency discharge is mostly happens, because instead of giving a DC bias here, your giving an RF signal. Therefore, there is a tendency of both the electrodes to change polarity cyclically, as the RF frequency is programmed at a certain frequency, at a certain occurrence rate.

In one half cycle of this, let us say you have a sine wave, which is a signal. In one half cycles, this side will get into a positive charge; this side will get negative charge. In another half cycle, this would interchange, so this becomes positive here and this becomes negative here. This particular circuit here is comprised of a blocking capacitor, which filters off all DC, as you all know a capacitor is an open circuit to DC - direct current. There is a blocking capacitor, which filters DC and only lets the sine wave or the RF signal pass through it.

Then, there is a matching networks here - the impedance matching network for reasons that I am going to illustrate in the slide probably. Then, there is a voltage source, which also gives some kind of a bias feed to this impedance network. We need to have a

variable inductor here; we need to really match the impedance to prevent reflection of the plasma power into this particular circuit. This is also based on what we call the maximum power transfer theorem. So, I am going to do this or illustrate this in the next slide.

In a nutshell, here radio frequency power is being used, in cases such as biasing voltage, where there are insulating materials on the cathode the blocking capacitor DC isolates the chamber. The inductor I is used to protect the supply v, as you can see here. The supply voltage v is used to provide bias to the LC circuit, which can act modifiable, so that we can have maximum transfer, from the capacitor here in the plasma system to from the RF signal generator here more into the capacitative plasma system, rather than going into the matching network here.

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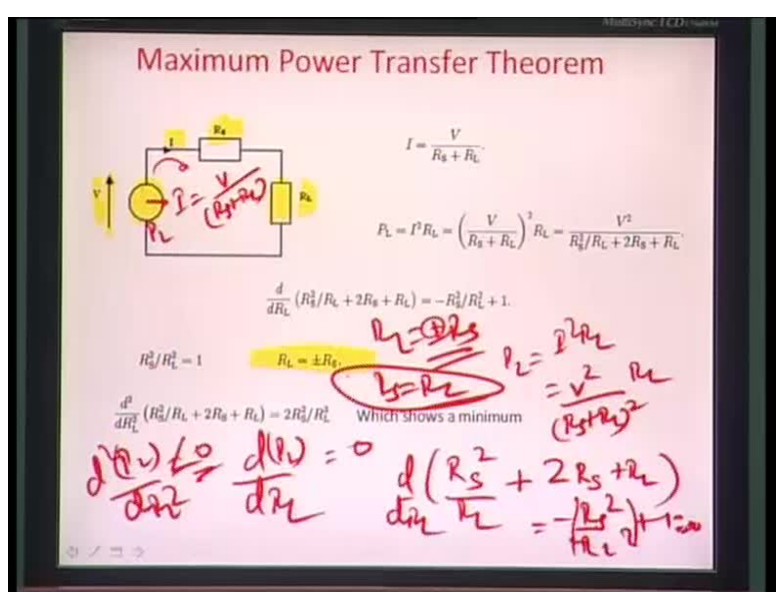

Let us see what this power transfer theorem is. So, it states that if you have a closed circuit with let us say two resistance units or two resistance impedance values, here as you are seeing R s and R l, where R l is the load resistance and R s is the internal resistance of the source - source resistance. You apply a voltage v across these two elements, thus generating a current I in the circuit.

For maximum power transfer from this voltage source v onto the load resistance, the condition that you have to meet is basically equality between the source resistance and

the load resistance. This is very simple to be illustrated as you are seeing here, the I here would be nothing but V by R s plus R l, the total resistance in the circuit by Kirchoff's law. Essentially, the power transferred P l from here to this is also written as I square times of R l, which is V square by R s plus R l square times of R l.

If you want to see the value of load resistance at which the power would be maxima or a minimal, you want to put the first derivative of P l with respect to R to equal to 0. In this case, as you do that the first derivative comes out to be equal to R s square divided by R l plus twice R s plus R l d by d R l, which makes it R s square by R l square with a minus sign plus 1. The second derivative here, the d 2 P l by d R l 2 would suggest that this particular term is less than 0, which means that it is a maxima.

Therefore, the only condition is if this is equal to zero, to meet the maximum power is that the R l should of course be equal to plus minus R s. Resistance being always positive, you have to make the source resistance equal to the load resistance for this power to be transferred in a maximum way from the power source to the R l.

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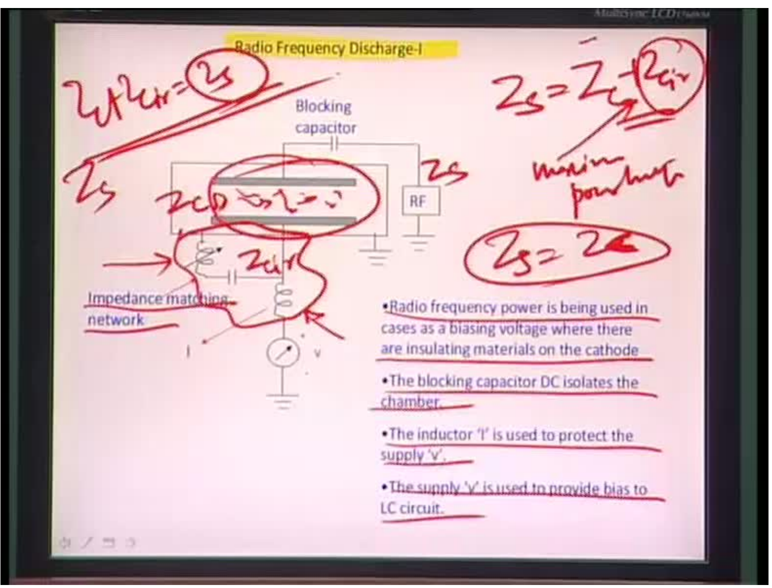

Now, in going back to this network here, let me just rub everything off here to illustrate a little bit of what goes on. Here also you need something called an impedance matching network, to match the overall criteria of R s equal to R l.

Let us suppose, you have a source resistance R s here of the R f signal and you have some kind of a - so this is actually an impedance, let us call Z s instead of R s, let us call it the impedance Z s. The total amount of load resistance is essentially the impedance here of the chamber, let us call it Z c and the impedance of this particular circuit here, which is Z circuit - c i r.

Essentially, we have to derive a condition Z s equal to Z c plus Z c i r for maximum power transfer to this part of the circuit, in order to do that you have to equalize this particular network. Therefore, you sometimes do not have a perfect Z s equal to Z c equality, one of the reasons is the quality of or the dynamics of the ions which are here in this chamber it is a dynamic process, you have ions, you have electrons and you have some gas molecules. You know, very dielectric constants, they may not be uniformly homogeneous as a property.

Therefore, the Z s here or what you call that the source resistance here or source impedance here is changing frequently. If your source resistance is same as the load resistance, only then you are going to have a maximum power transfer. However, if the load resistance here is changing with this varying non-homogeneous dielectric constant etcetera, then you do not have any maximum work transfer. So, this Z c i r gets into the picture. You basically try to change the impedance of this whole circuit by matching the impedance network in a manner, so that Z c plus Z c i r becomes equal to Z s. So, maximum power can be transferred onto the chamber from the power source.

That brings us to the end of this particular lecture. We will start with some other plasma generating processes, like how RF can be generated or how magnetically enhanced plasmas can be generated and used in next lecture; thank you.