Optoelectronic Materials and Devices
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Lecture - 40
Organic Solar Cells and Organics Thin Film Transistors

Today, I am going to introduce two more organic devices to you, organic photovoltaics, say Organic Solar Cells and Organic Thin Film Transistors. So, let us start with organic solar cells.

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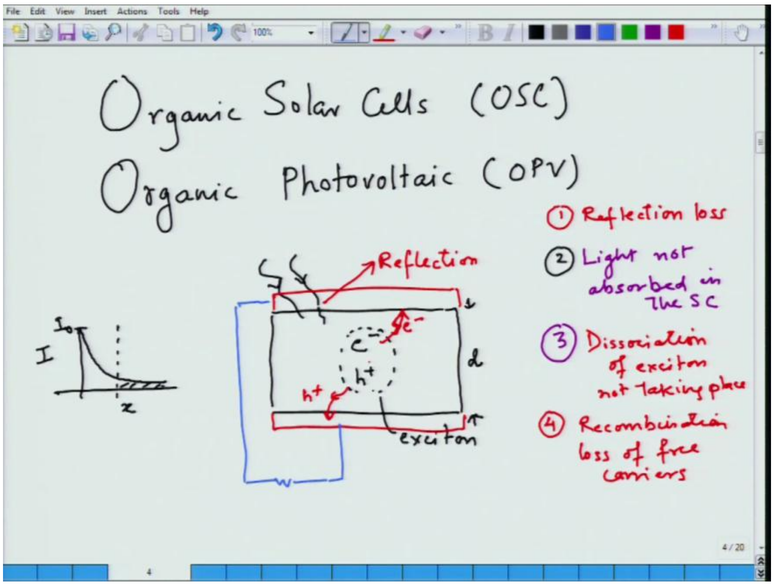

Organic solar cells and often (( )) OSC, some people also write for the same device organic photovoltaic and used the acronym OPV, but basically the device is a diode which works like a organic cell. Now, we have discussed earlier inorganic solar cell, which was made by using a pn junction. So, there was a built in field, which was used to take the absorbed photon, convert them into electron and holes. And then the built in field was used to take them to the respective electrodes and generate electricity.

In the case of organic solar cells, we we do not make pn junctions in the same way, we basically use the work function of the metals to connect to the HOMO and LUMO of the organic solar cell. So, let us start from looking at, what is happening in the organic solar cells, so we will start with the organic semiconductor. So, if I have organic semiconductor, and we start with shining light on it, so which is will be the solar spectrum in case of a solar cell.

Then this light will be observed absorbed by the organic semiconductor and it will create a electron and hole and that electron and hole is likely to be bound to each other and form a exciton. Now, in the process let us see, what are the losses that take place in the organic solar cell, when the light shines on this semiconductor on or in this device which we will build a little later, there will obviously be some amount of reflection that takes place, at whatever the surface from which the light enters.

So, the first type of losses, that you can consider as challenge to organic solar cells are the reflection loss or sometimes, people talk about it as the coupling of the light to the with the device and then this light is going to get absorbed. But, it would depend, what is the thickness of this absorbing layer, that will decide how much light is absorbed. Because, if you recall the optical properties discussion, we talked about that the light absorption is follows the beer’s law which says that, if I plot intensity as a function of x then if the light entering is I naught, it will be absorbed maximum close to the surface and then exponentially decrease as we go in.

So, if I want theoretically to absorb all the light, I have to have a infinity of thickness of this semiconductor material, which is not possible. And hence, this will always be some finite value and there will be some losses, which will not be absorbed. So, the second loss would be the incident light, which is not absorbed in the semiconductor and so we are now left with that part of the light, which is successful in creating an exciton.

Now, this exciton is a neutral species, it is it has one electron and one hole and in order to collect the electrons and holes at the two electrodes, we have to have dissociation of this electron. So, the third possible loss in this material is dissociation of exciton not taking place which basically means that, exciton which is formed recombines electron and holes, recombine and the exciton is lost. So, that could take place which means, exciton which was generated could not be could not result into electron hole, free electron and holes which could be collected at the two electrodes so that that would even another possible loss.

The next one would be, once these electrons and holes let us say become free and the exciton is dissociated, these electrons and holes have to be collected at the two respective electrodes. So, let me mark the electrodes as on this organic solar cell, one side where electrons are being collected and on the other side, the holes are being collected. Now, there will be another loss process because in the process, from where this electron is generated and moves to the cathode, it is possible that it might encounter another hole and get annihilated.

So, there will be recombination loss on the way, recombination loss of free carriers that could lead to another loss. Now, after all these hurdles, if electron and holes are successful in getting to the the two electrodes then we will have electricity in the outer circuit. So, there will be a voltage generated and if I have a load, I will be able to flow current in the outer circuit and this would be my organic solar cell.

Now, in in order to understand what are the issues in the organic cell? Let us understand the difference in the excitons in the organic and the inorganic semiconductors. So, if we look at the challenges, the first two challenges of organic solar cell are same for inorganic and organic, which is coupling of the light and how much absorption is done.

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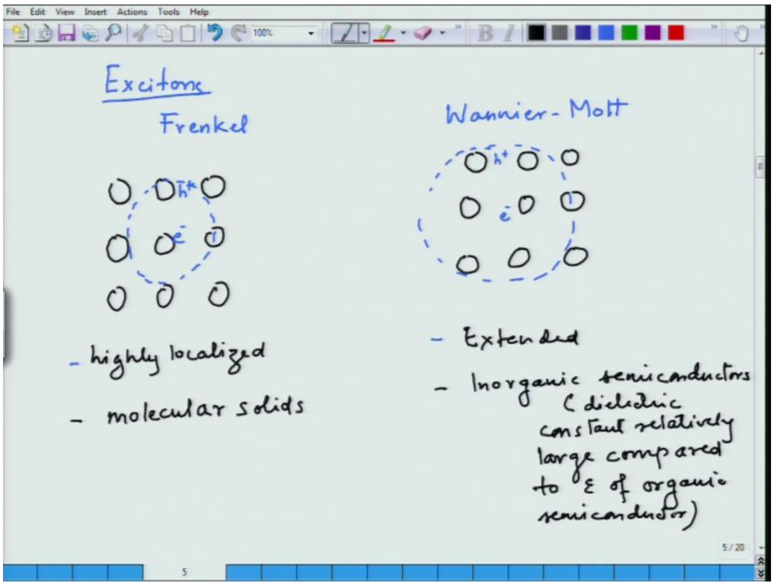

But, excitons have a very different behaviour in organic and inorganic semiconductors and they, because of their different behaviour they also have different names. One type of excitons are called Frenkel excitons and the second one is called the Wannier-Mott exciton, after the name of people who found them out and discussed, what is the difference between the two. And the Frenkel exciton is the one, which is common in organic semiconductor.

In this particular case, if let me draw may be the molecules drawing them in a round shape, I think of them as a molecules of the organic material, and then in this particular material, if I am creating a electron and a hole pair. Then, this electron and hole pair will remain associated with each other in a influence circle and that is very tightly bound to each other.

So, this particular type of exciton is highly localized, it is highly localized and this is a one which is normally found in molecular solids. That is a case of organic semiconductors where, the solid is made of molecules held together by Van der waals forces. The second type of exciton, again in the case in this case, you can think of either atoms or molecules in case of organic semiconductors, the second type of exciton are the ones, which where electron and holes are associated with each other but it is a very large influence area.

So, they are not localized, they are extended they are extended and these are the ones, which are commonly seen in inorganic semiconductors. Why the nature of the exciton is so different in the two cases, in the in this case it is very electron is very tightly bound to the holes. So, which means, if I want to create a free electron and hole in order to collect it in a organic solar cell, I I need a lot of energy to dissociate that.

On the in the other case, in organic case, it is not tightly bound to electron and holes are not tightly bound to each other and hence, I can easily dissociate them and collect them at the two electrodes. And the reason for that is, in inorganic semiconductor, dielectric constant is dielectric constant of inorganic semiconductor is relatively large compared to dielectric constant of the dielectric constant of organic semiconductor.

And this leads to the reason, why the excitons are much more tightly bound in the organic semiconductor and hence, this is a problem which we did not discuss in case of inorganic solar cell. In organic solar cell, one of the challenge is to dissociate the excitons, so that we can have free electrons and holes and then before recombining they get collected by the two electrodes.

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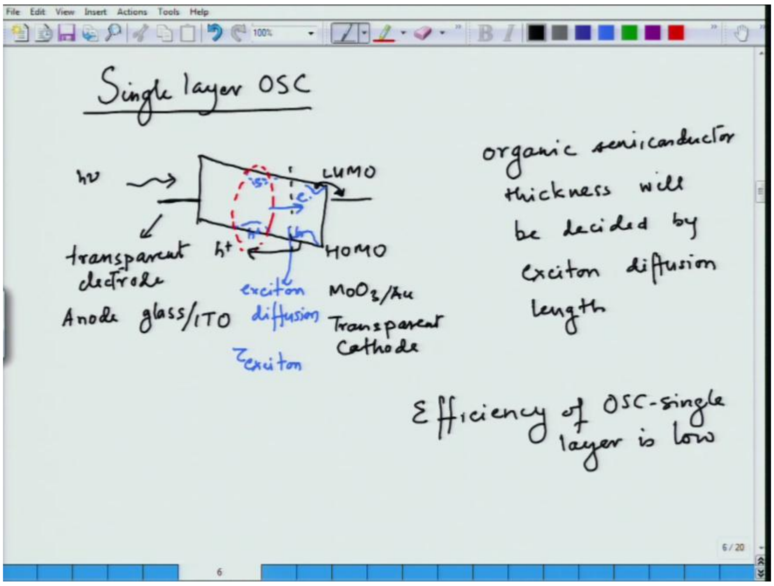

So, in order to do that, we look at now some simple organic solar cell structures and try to see, what will happen. So, let me first discuss a single layer organic solar cell, so as we have discussed the diode structures, in this particular case we have two electrodes with different work function, one anode and cathode in equilibrium. We will show the two electrodes having the work function is equilibrated across the semiconductor and because of this, there is band banding, the built in potential in the organic semiconductor.

The HOMO the HOMO LUMO are bent, so this is the LUMO lowest unoccupied and the HOMO of the semiconductor and let us see how, what are the issues in this particular device. So, if I shine light and let let this be my transparent electrode and it is possible for me to have either anode as transparent anode, which is the case we have been discussing so far where we used the system for the anode, the glass ITO combination. But, recently there are many more papers where, they use the cathode also as being as transparent and rather than the anode.

So, there are materials systems which will go for transparent cathode an example, there might be moly oxide gold combination, this should be a transparent cathode. So, the light will be will be coming from this direction onto this the semiconductor once it gets absorbed then we have created a electron and a hole. And I am making these dash line to show that, the energy of this electron hole associated with each other is less than, as if they are free in the HOMO and LUMO bands and because of this they are bound.

Now, since the binding energy is very large, this exciton does not get dissociated easily but what it can do is, it can diffuse in the semiconductor so it will diffuse so this would be known as exciton diffusion. And depending on what is the lifetime of the exciton, the exciton lifetime which basically means, exciton electron and hole pairs before dissociating combine and the exciton is lost. So, if the lifetime of exciton is very small then there will not be appreciable diffusion.

So, we need to make sure that, the diffusion is the diffusion length is calculated for a given exciton. Now, in that length, this exciton is going to diffuse and may be come to this point at a electrode, it could go all force on others direction also. Now, this electron and hole will then get dissociated such that, the electron is collected at this end and the hole will travel to the opposite electrode. Now, why the exciton diffuses upto the electrode and dissociate because here there is a difference in the energy band diagram and that acts as a catalyst for dissociation of the exciton.

So, it looks for this difference between the energy level at particular interface, which helps the dissociation of exciton. Now, there are problems here, if I make the device very large, let us let us say to absorb more light, what can happen is that, the exciton which is generated here, it is lifetime is small and it only diffuses to a value, which is may be here where, it does not dissociate and gets lost. So, the exciton has to diffuse upto the cathode level in order to dissociate and be collected as free electron and hole, and that is the reason why, the the organic semiconductor thickness cannot be very large.

Organic semiconductor thickness is being decided by, thickness in this single layer device will be decided by exciton diffusion length, which is the distance the exciton will travel before it is annihilated every distance. So, it cannot be very large, it has to be within the diffusion length of the exciton and in this process, since and now this electron, which is getting collected at the anode, it can may be find a electron if there are dissociation then it can also be lost on the way so there may be some more losses. So, you can see in this particular single layer OSC, generally efficiency of solar cell is very low, OSC which is single layer is low.

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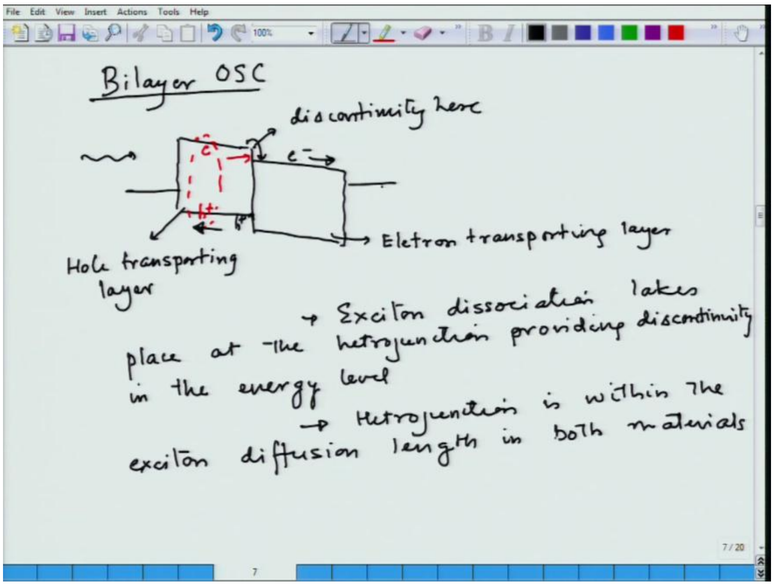

So, to circumvent those problems, the second structure or another structure which has been seen is the bilayer organic solar cells. And in the bilayer organic solar cell, we basically use two organic materials so once again, I have my electrodes and here, in addition to the active layer is made of two organic semiconductors, which provide a discontinuity of the HOMO level at this point. So, there is discontinuity here and the advantage of this is that, when the light is absorbed by the semiconductor and if a exciton is created here.

And if it diffuses in this direction, it gets dissociated at that at this discontinuity and then the electron is being collected here and the holes at this point are collected on the opposite electrode. Generally, because of this nature, the way it is designed, this would be a electron transporting layer semiconductor, it should have a high mobility for electrons and the other one will be a hole transporting layer. So, the semiconductors are chosen such that, they make it easier for the free electron and holes to be collected by the electrode.

At the same time, this continuity allows dissociation of the exciton before much before it comes to the cathode. So, one can have the exciton diffusion length, which is half of the device length and the light can be absorbed throughout this device structure. So, by adding a bilayer of material, which are of a different nature in terms of mobility of the carriers, one is able to improve the efficiency of the device. So, this is bilayer organic solar cell, it ensures that exciton dissociation takes place at the heterojunction, providing discontinuity in the energy level.

And this heterojunction is within the the design has to be such, that the heterojunction is within the exciton diffusion length in both materials. Now, by doing this bilayer then one improves the collection of free electrons and holes, and the efficiency of bilayer organic solar cell is better than a single layer organic solar cells. Now, this was possible but it is more difficult to make bilayer solar cells, so the next design which ensures that, one finds interfaces for exciton diffusion close to the exciton generation.

And the second structure which is very common is using the bulk, it is called bulk heterojunction organic solar cell and so in design, it is simple enough where, we use in the centre, we have like a single organic solar cell. But, it is blend of two, it is blend of the electron transporting semiconductor plus the hole transporting semiconductor and then we can just add the electrodes to that, to make the device.

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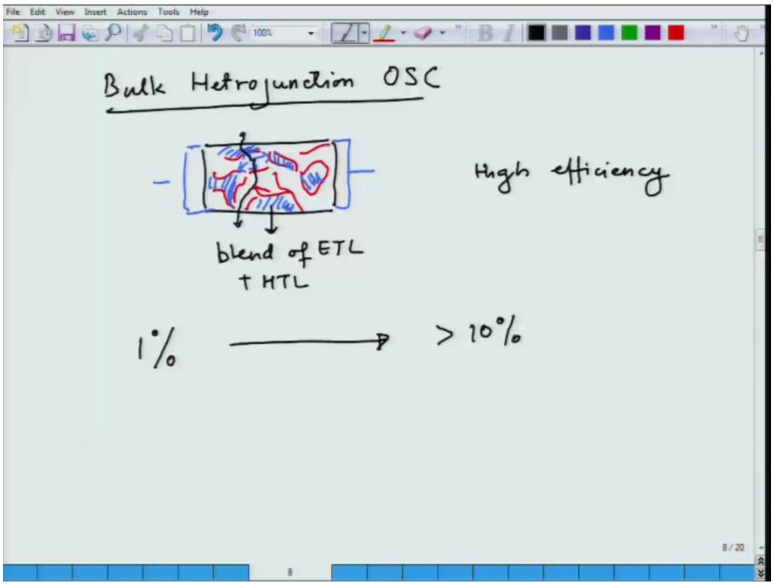

So, by using the blend what happens is that, now in this particular blend, I can think of the semiconductor, the two semiconductor being intertwined and randomly distributed. So, each orange line is a interface between two type of semiconductor and what this allows is that, if a exciton is let us say, generated at any point here, it has lots of interfaces at which it can get dissociated. So, it can diffuse in any direction and within the diffusion length, it is likely to find a interface where, it will be dissociated and then that electron will be collected eventually by the two electrodes.

So, it has increased the surface of the junction of the two semiconductors by blending them together. Now, that surface the junction surface of the electron transporting and hole transporting semiconductor is much, much larger than, as if you are making the bilayers. So, that improves the efficiency even further and this particular organic solar cell have shown a fairly high efficiency. Now, that we are discussing the point of high efficiency, the initial organic solar cells, that were built at very, very low efficiency which was single cells.

And then the efficiencies were in the range of about 1 percent in early 2000 and that number has been successively challenged and today, solar cell even greater than 10 percent, organic solar cell greater than 10 percent efficiency has been produced. So, you can imagine the kind of excitement, the kind of research and development that is going on in terms of finding materials, we shall give you better efficiency. Because, as we mention there are different losses, first loss would be working on the device structure so that, reflectivity is less. Second would be working on materials which will absorb more, third would be on the design side such that the interfaces are such, that they will allow dissociation of excitons and then collection by the respective electrodes.

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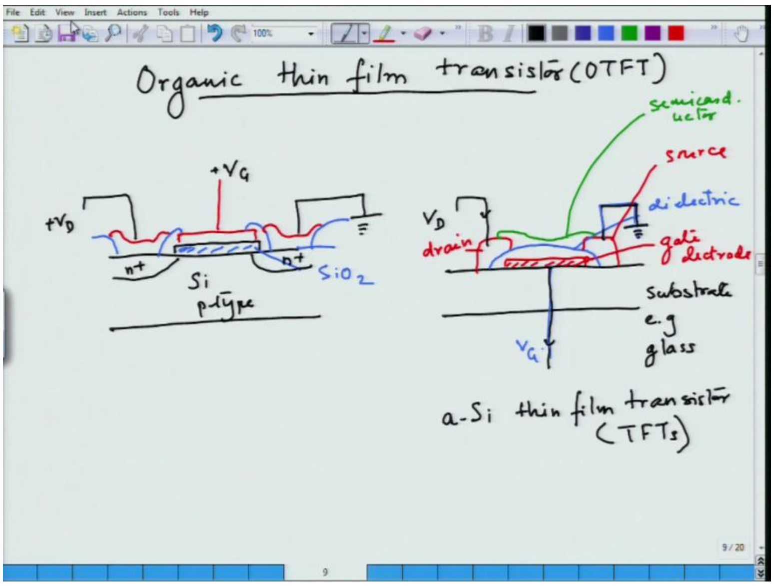

So, there is enough work going on here, that in last decade we have seen almost 10 times improvement in these devices. And since there is a scope, as we discussed earlier for organic electronics to be extremely low cost, there is lot of excitement in developing these organic solar cell for applications for energy generation. With this now, I will like to go to the second device that I want to discuss, which is organic thin film transistor?

First what we discussed earlier in terms of transistors was that, the more common transistor today when applications is mosfet. And if you recall we discussed for making mosfet, we normally start with silicon as substrate and then we going to oxidize it, this is the oxide SiO 2. And I am going to start with normally p type silicon for making a n mosfet and I will create the drain and source contact by doping it n plus so that, I will create inversion layer here and then my mosfet will work.

I am going to make contact to the gate using a metal and I need to make contact to the drain and source so I am going to make contacts to the drain and source here. So, in this particular case, we normally define this as source, this was my gate voltage and this was my drain voltage applied, this was my mosfet where, I started with the semiconductor built on it and created a mosfet structure. Use the inversion of this structure to create a channels as a third terminal and the voltage between the source and the drain is then used to flow the current and I have the switching behaviour for a transistor.

Now, from mosfet, first we go to what is thin film transistor, now in this particular case, I have to charge with bulk silicon and I will I waste a lot of silicon here. Because, the silicon wafers are something like about 500 micron thick and this layer, that I have drawn is about 1 micron. So, this is not too scale obviously, this layer is very this silicon is very thick and the the whole device is made in few microns on the surface.

So, I am wasting a lot of silicon if I look at it, that is one point and the second point is, if I want to make this transistor as a switching element on any surface, on a any insulating surface then I need to first deposit silicon. And that lead to development of a different type of transistor, which is known as the thin film transistor and in this particular case, the thin film transistor uses any substrate, I can make it on any substrate. So, the substrate may be a glass so for example, it could be glass and I will be making a transistor on it.

So, first I will make deposit a metal, this is my gate electrode then I will deposit a dielectric on it, again these are all thin films of few microns or in sub micron range, I have a dielectric film on it. And now, I want to deposit the the silicon on top of it or semiconductor, that I am going to study. So, I need to make then again the contacts for the source and drain, I will make source source and drain here, this is my drain and this would be my source then finally, I make the deposition of the semiconductor.

Now, this is kind of a inverted mosfet, as you can see this is my gate, this is where I will apply the gate voltage, this point is my source, make it black clarity, source might be grounded and here, I will apply my drain voltage. So, what I have done here is, I have not started with silicon just by using thin film deposition techniques. I have created a transistor, which is which is what we called field effect transistor and I have created a gate effect between the dielectric and the semiconductor here.

So, this is how, we go from mosfet to thin film transistor and very common example for for thin film transistor is amorphous silicon semiconductor based thin film transistors. These are very commonly used in many display application known as TFT's and that is why, when we change amorphous silicon by a organic material, becomes OTFT so this is a OTFT So now, let us see, how a organic OTFT will work, this works inorganic works very similar mechanism, in which the mosfet works.

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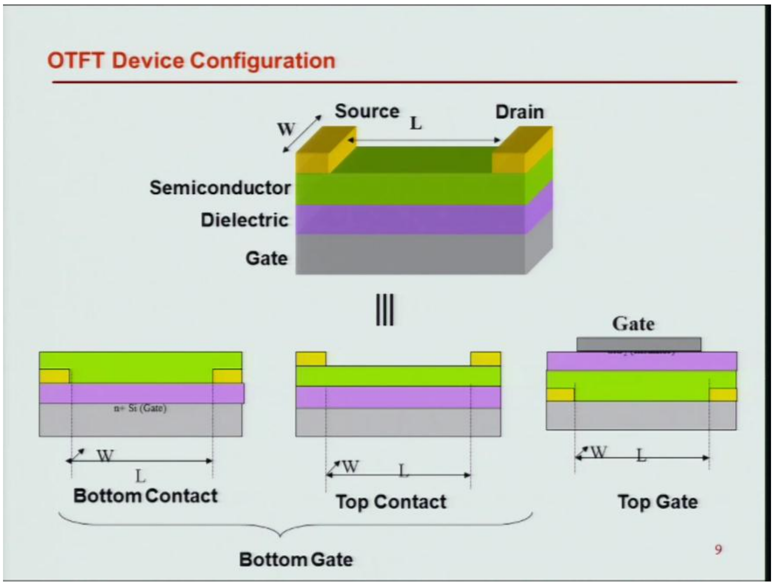

The only thing here has happened is, my structure I have inverted the structure now, the gate is at the bottom and source and drain are at the top and semiconductor is the is at the top. So, if I now change the semiconductor to to organic semiconductor, I will have a OTFT so let me show you some example of OTFT structure, there are different configurations one can see. And so I can make OTFT in various configuration, as you can see this is now, we have the gate which would be on some substrate then the dielectric layer then on the top a semiconductor layer.

I can have a configuration, in which my source and drain are at the top source and drain are at the top and this is known as the top contact OTFT. I can have another configuration, in in which the source and drain are deposited at the interface between the dielectric and the semiconductor and that is known as the bottom contact OTFT. And I can even further change it, rather than having gate at the bottom, I can have a structure in which the gate is placed at the top and that is known as the top gate. And one can think of many such many device configuration, in which you can situate your source, drain and gate with respect to each other ensuring that, there is a channel made and you are collecting carriers, as a function of different gate voltages, let us discuss then how these devices operate.

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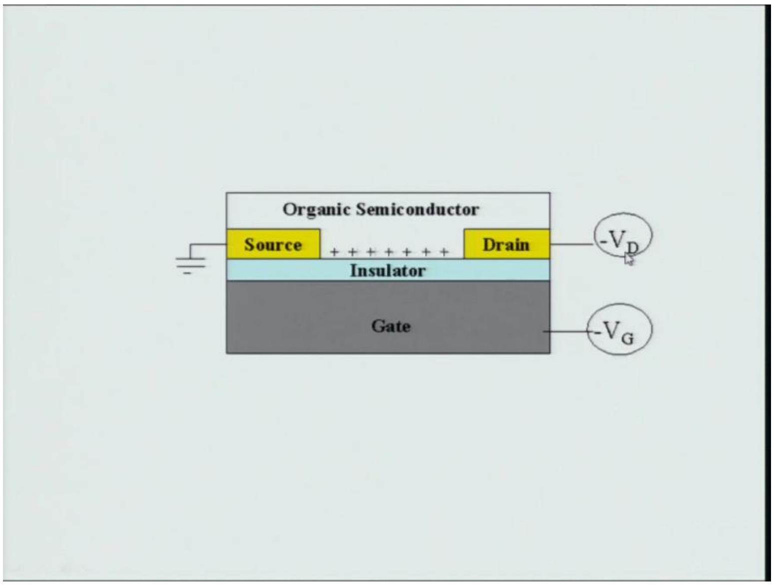

How does this device operate, in order to look at that, let us find a way of looking it so this is our bottom contact organic thin film transistor. Here, I am showing a transistor which is made on a highly doped p silicon such that, it is becomes almost like a conductor so it is a kind of degenerate semiconductor. On top of that, so this is not the semiconductor, this is a this is this you can call as gate electrode in this particular device.

And the insulator and the gate voltage will be applied through the p silicon then I have this bottom contact configuration, in which I make the drain and the source and then I deposit my organic semiconductor on top. Now, if I want to go and apply apply a make the source at the ground and apply a gate voltage then what will happen is with respect to the source, there is a voltage applied here. There will be some carriers, which will be injected into the semiconductor and because of a negative gate voltage, they will start getting accumulated at this interface.

Now, if I will apply a drain voltage, these carriers will start moving and I will have a drain current and this is how, a organic thin film transistor will work. There is a there is a distinct difference here, from the inorganic semiconductor where, the carriers which come at the channel are generated, because of the depletion or accumulation affect in the organic semiconductor. But, if you will recall in our organic semiconductor, there are no free carriers, assuming if there are no impurities or no doping and which means, that all the carriers which come to the organic semiconductors have to be injected.

So, in this particular case, the carriers which form the channel are coming from the injection from the source. And then these carriers can be moved by applying a drain voltage so when we look at the behaviour of the organic semiconductor, it would be very much similar to very much similar to the mosfet.

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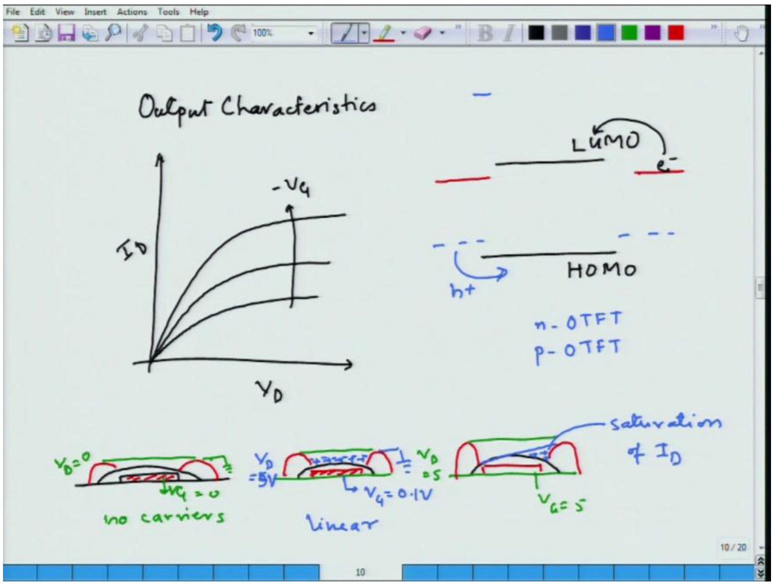

So, in this particular semiconductor, when I plot the output characteristics, output characteristics are plotted with respect to the applied drain voltage at different gate voltages. I am measuring the drain current then depending on how much gate voltage I will apply, there will be accumulation of the carriers and at different gate voltage, I am going to get a drain current and there will be also seen a saturation.

So, this is the way where, V G is becoming more negative so V G is becoming more negative and what is happening in the in the device here is that, I have the gate and the dielectric and then the two drain and source and the semiconductor. So, when there is when there is a V G applied so initially there are no carriers no carriers. If I have if I have not my V drain is 0 and V G is 0, the sources any way grounded at that point, there no carriers in the semiconductor and I have no current.

When I go to a very small value of V G at that particular point in this semiconductor I have a because I have V D is still 0 but I am applying a small V G. V G is let us say, 0.1 volt, source is at the ground and V D is also very, very small let us say, about 5 volts. In that case, I would see a drain current, because of the accumulated holes that are there in the semiconductor and I would see a increase in the current and this is a linear region.

Linear region when I have small V G and small V D, when I increase the V D further then again just like just like in the mosfet, I am going to find a saturation of the current. Because, in this particular case, when V D is also 5 and V G is also 5, at that point the channel is only there is no channel close to the drain and the channel is only limited here. And this leads to the saturation behaviour, saturation of the output characteristics, saturation of I d.

So, although the OTFT works in a very different way, we do not have a inversion layer as like inorganic as in as in inorganic semiconductor, it works by injection of carriers into the semiconductor. The behaviour of the output characteristics is very similar and that is the reason, why many times the analysis of OTFT is done assuming ideal mosfet behaviour. And we say that equivalent mobility to a mosfet of a OTFT is this and equivalent threshold is this, although the mechanism of threshold and other things are not same in case of OTFT.

In this particular material then now, we can also plot the transfer characteristics, if we if we plot if we just look at the HOMO LUMO of the semiconductor here, what is happening in the channel. This is the highest occupied molecular orbit and the lowest unoccupied molecular orbit. And if I have my drain and source material, if I am going to use a low work function source material then it will be the electrons, that is that are likely to be injected.

On the other hand, if I use a material which is high work function then it will be the holes which will be injected. And then this will be a n or p channel depending on, what metal I use for drain and source for a given organic semiconductor. So, as you can see, although the the terms remain the same, the n channel or the p channel, the reason why it is a n channel or p channel is not decided by the doping of the semiconductor but by the work function of the metal.

So, I can have the same transistor and in this particular case, if I am injecting holes in the semiconductor, it is going to be a p type behaviour for the organic thin film transistor. On the other hand, if I change my metal and I now inject electrons in the organic semiconductor, it is going to work like a n channel semiconductor. So, it is possible to have both type of n type of OTFT n channel OTFT and p channel OTFT and that depends on the metal, that I will use for injecting the carriers to form the channel.

With this, I hope we have shown you the a very new field of electronics, which is organic electronics. The material is very different from inorganic electronics but within the given specification, we can make all possible devices that are that can be made organic solar cells, organic light emitting diodes and organic thin film transistors. Organic light emitting diodes as shown in my presentations that, they are already a commercial device, it is already a successful device.

Organic solar cells have a still lot of research and development going on, in order to improve efficiency and mainly to improve lifetime. In organic thin film transistors, again it is a successful device and it has been shown in prototype application. But, still lot of work needs to be done, when it can be competing with the amorphous silicon thin film transistors for making electronics much, much cheaper.