Physics of Functional Materials and Devices

Prof. Amreesh Chandra

Department of Physics

Indian Institute of Technology Kharagpur

Lecture – 44, Week 11

Solar Cells – I

Welcome to the second lecture of week 11. In the previous four lectures that is the first lecture of this week and the final two lectures of the previous week, I have been talking to you about the need for energy storage devices. We have been talking to you about the requirement for such storage technologies because the renewable based generation units suffer from an intrinsic limitation and that is the intermittent character. But as we move forward renewable based generation units would be an integral part of our energy landscape. One of the major area which India is focusing on is solar cells and let us today start our discussion on the use of these functional materials in the next generation solar cells which are being proposed and hopefully in couple of years time you will find that these would be in market. So, in today's lecture what I will do? I will give you a brief introduction to the concept of photovoltaics, how based on the materials the class of solar cells are defined or the generation of solar cells are defined.

So, generation 1, generation 2, generation 3 and most probably we are in the fourth generation solar cells which are based on perovskite based materials. For that we will also require to talk to you about the use of semiconductors, why they are essential to have the formation of p-n junction that is going to be utilized in solar cells. So, we must also have a quick overview and revision in the field of semiconductors. If you look into the photovoltaic classifications, you will find that the classification of various solar cell technologies are based on the materials.

Are not called as solar cell 1, solar cell 2, solar cell 3, solar cell 4 because you have some time blocks in which they are being defined. They are being defined as per the materials which are used to fabricate those kind of solar cells. For example, the first generation solar cells are those which are fabricated using crystalline or polycrystalline silicon. Generally, their thickness is more than 100 μm and the typical efficiencies which are there in the solar cells being commercialized and sold in the market range from 20 to 25 % (+-) is the symbol which I have used here for specific reason. Because if you go into literature that is the research which is going on still in this area you will find that there are people who are reporting slightly higher efficiencies If you go to market then you may find the actuals are slightly less than this value, but the typical values which we are talking about for the first generation solar cells based on crystalline or polycrystalline silicon is around 25 %.

Then came the second generation solar cells where the thickness is of the order of 1 μm. The efficiencies are of the order of 22 % plus minus again you may find some reports giving you slightly higher values or you can have certain reports which give you slightly lower efficiency values. These are based on amorphous silicon or CdTe, CdS, gallium arsenide or CIGS which is standing for copper indium gallium diselenide. From there people moved on to the third generation solar cells which are having the thickness of the PV cell of approximately 1 micrometer or slightly less and those are based on organic compounds and therefore, they are called as organic solar cells. If you have another set of materials which are being used to fabricate the third generation solar cells, those are dye sensitized solar cells. So, D stands for the dye which will be actually absorbing the light they have a thickness of slightly more than 1 micrometer and the efficiencies are around 20 % (+-).

The advantage of these solar cells they are quite flexible and then they have their own advantages, but because of the nature of the materials which are being used to fabricate these solar cells they have their own intrinsic limitations. Probably we are in the fourth generation photovoltaics where we are talking about perovskite based solar cells. As the name suggest here we are going to use the perovskite materials. What are perovskite materials? the structure which we are talking about are ABX_3 kind of structures. So, this is what we had been studying earlier again the famous crystal structure comes back and then it is being utilized in the quite popular and futuristic solar cell technology based on these materials.

They already have very high efficiencies there you are talking in terms of efficiencies which are 28 % (+-). So, you are already competing with those technologies which were being researched for around 40-45 years and within the time span of 10 years you have reached the efficiency parameters that were being reported in the solar cells which are being investigated for last many decades. So, the perovskite based solar cells are also becoming quite important, but you can clearly see that the classifications are all based on the nature of materials and we will see how the materials which we have used or talk to you about them in this course are going to becoming important for these solar cells. Before actually moving forward, let us quickly try to build our understanding about this technology and see can we understand what is actually a P V effect with respect to the photoelectric effect which we all understand from our school days. So, if you have the photoelectric effect what do we have? We have the Einstein equation that describes the emission of a photon from a metal plate.

Now, you can clearly see that the maximum energy of the photon would be given by (hv-ϕ) where ϕ is the work function and hv is the energy of the photon which would come out. And this is the typical setup what you have you have the potential in a evacuated quartz tube. So, you have two electrodes and when you have the a light falls on the plate then it emits an electron from the metal surface and you have the flow of current because it is photon induced. So, it is called as photoelectric effect. Now, if you compare this same performance and see what is going to happen in terms of the photovoltaic effect.

What you take? You take two semiconductors a p-type and a n-type. So, if you make a p-n junction there are various methods to make a p-n junction, then at the interface we know that there would be a depletion layer which would form. and these charges which are annihilated within this deposition layer. If you have energy sufficient enough to break the hole and electron pair, then what will happen? The holes will move towards the p type and electrons will move towards the n type and you will have the flow of current. So, you break the electron hole pair which were each other at in the depletion layer as electrons move from n to p type and then holes migrated from p to n type that means, region from higher concentration to region of lower concentration And, in between because of the charge compensations they go to the state where the hole and electron recombine.

So, they have these recombination taking place and if you can break these electron hole pairs once again then that would lead to the flow of current. So, obviously, the process occurs near the depletion layer. So, you what you need to do you if you take into the concentration. the way you will fabricate the solar cells. So, this is a typical way you will be fabricating using a screen printing technique.

What you have? You have the back electron, then you have the p-type region, then you can have the deposition or you can have other techniques by which you actually have the n-type layer getting diffused inside the So, there is a diffusion, but when there is a diffusion at the interface you have the formation of the depletion layer. So, you have n type being grown on the p type and you have the depletion layer formation at the interface. Then what you do you just simply have to have the gridded electrodes. light can pass through if you have the full surface as electrode then what will happen? The light cannot pass through and hit the depletion layer. So, you have these grid electrodes so, that the light can pass and cross the thin n type layer and hit the depletion layer.

So, then you just need to connect the the grid electron with the back electron through an external load and when you have the light shining the electrons will flow from the grid electron to the back electron and that would lead to the flow of current. So, is this a very similar concept which you can see is that when if you have a photon which is incident on a semiconductor material then electron may be promoted from the valence band to the conduction band and what will happen if the photon has the energy h nu that is greater than the band gap. then you will have the transition taking place and you will see that there is a flow of current. Now, if you look into the overall process you will find that things which we discussed is basically being driven by the inbuilt electrical field across the depletion layer and because of that the electron move towards the n type and holes move towards the p type material. Now, the electrons can flow around the external circuit through the external load from n type to p type and where they recombine with the hole and you again reach the condition of charge neutrality.

So, the material becomes stable as a result you have the electrical power being delivered to the external load. So, you do not change the charge neutrality condition. Now, the moment we start talking about band gap. we have seen in the free electron model as to why there is a origin of band gap in solids. In semiconductor you have the band gap in the range of let us say 0.

1 to 3 eV. There are two types of semiconductors intrinsic semiconductor as well as extrinsic semiconductors. if you look into the intrinsic semiconductors you have them as silicon germanium and if you look into the extrinsic semiconductors you can have two types the n type or the p type. So, if you want to have n type material that means, where the electrons are the majority charge carriers, if you have p type then the holes are the majority charge carriers. If you want to make a intrinsic semiconductor to an extrinsic semiconductor then either you will dope it with a pentavalent impurity or a trivalent impurity.

If you have a pentavalent impurity going in then you get a n type semiconductor and if you have a p type semiconductor which is required then you will use a trivalent impurity. So, by choosing the right top end what you can do? You can tune the band gap. So, you can tune the band gap of the semiconductors. This has been explained quite clearly in the free electron module. or the nearly free electron model.

So, you can tune the band gap quite easily by changing the dopant and its concentration. If you look into the intrinsic semiconductors. So, what you have for example, if you take silicon or germanium you can take any one of the examples at temperatures above absolute 0, what will happen? It will have finite number of thermally generated electrons in the conduction band, because you have the energy kβT and you will have the corresponding number of holes in the valence band. The densities of these charge carriers would be small because the thermal energy kβT of the electron is quite small compared to the band gap and the probability of electrons jumping from valence band to conduction band is low because of this low energy associated with the electrons and hence the charge carrier concentration in the conduction band is low in the case of intrinsic semiconductors. So, what you need to basically do? You need to somehow modulate this condition and ensure that the charge carrier concentration can be modulated.

So, what you simply do? You have the extrinsic semiconductors. here either you dope it with pentavalent or trivalent impurities and then you can reach either n type or p type semiconductors respectively. In n type you have the abundance of electrons and in p type the holes are the majority charge carriers. So, what are you going to do? You are basically going to change one of the silicon atoms with a donor atom. That means, you will have a pentavalent atom that will lead to the extra spare electrons and that is why you will have the n-type semiconductor.

In this case, we just took an example of the concentration. that one of the atoms of silicon is being replaced. But if you look into the concentration variations or the doping profiles you will find that this can be changed quite significantly from low concentration to higher concentrations and that would lead to the different orders of majority charge carriers in these semiconductors. and hence what will happen? You will have the donor levels which are intermediate to the initial case where you had the intrinsic semiconductor and hence you will find that the number of electrons in these donor levels increase and you have higher probability of these charge carriers becoming mobile. and because of this mobility they move to the conduction band and then they can take part in the conduction mechanism.

Quite similar in case of the p-type what you will do? You will basically have the trivalent it opens and you will get a condition where a hole is actually get stabilized and then you will find that the acceptor level is nearer to the valence band. and because the of the acceptor level being nearer to the valence band certain electrons can jump from the valence band to the acceptor level and leaving behind the holes which become the majority charge carriers in the p type semiconductors. As you will find because of this donor and acceptor levels you will find that the Fermi in the p-type is nearer to the valence band and the Fermi level in the n-type is nearer to the conduction band when you are talking in terms of n-type semiconductors. But when you have a p-n junction which is formed what you will find that as this junction is formed the double layer of charges cause an electric field. to be set up across the junction.

So, you have this double layer of charges which are being formed. At equilibrium there must be no net current flowing across the p-n junction and what is the thing which will counterbalance the diffusion current is the drift current. So, you will have the drift current which will counterbalance the diffusion So, if the drift current is going from positive to negative side then you have the diffusion current going from the negative to positive side. Now, you can polarize this condition and you can have two possibilities either you can have a reverse bias or you can have a forward bias. What will happen in the reverse bias? You will find that the junction width actually increases in comparison to what happens in forward bias where the depletion region width is actually reducing.

So, the case where we talk that is reverse bias what is happening that the diffusion current is much lower than the drift current. and the majority charge carriers are therefore, they are pushed away from the junction. And if they are pushed away from the junction that means, the width of the depletion region increases. The bias voltage V drops across this high resistance depletion layer because it is a region where you do not have mobile charge carriers and therefore, it is acting like an insulating layer and therefore, the voltage drop is occurring in this high resistance depletion layer. What happens? This leads to the increase in the height of the potential barrier which was initially V_0 and it takes it to $(V_0 + V)$.

The diffusion current essentially becomes quite small and to most approximations it is taken to be 0. just the opposite case when you have the forward bias what happens? The diffusion current is much larger than the drift current and the majority carriers are pushed towards the junction and in that case what will happen? The width of the depletion region actually reduces. if that happens the height of the potential barrier which was initially V_0 is reduced and it becomes $(V_0 - V)$. If you plot the I-V characteristic of a semiconductor p-n junction you have in the forward bias and in the reverse bias the magnitude of current and the dependence of current I on bias voltage is given as $I = I_0 \left(e^{(eV/kT)} - 1 \right)$, where T is the absolute temperature and k is the Boltzmann constant. Once you have the Fermi energy in a p-n junction you will see that it is constant throughout the semiconductor in an unbiased p-n junction.

So, you have an interface which is formed and therefore, there should be wave function matching and which means there is a Fermi energy level which is constant throughout this semiconductor p-n junction when it is in a unbiased condition. There is a step change which is equal to eV_0 in energy between the n-n p-type region. So, you have a change in the energy when you go from p type to n type. In p type what you see the Fermi level is nearer to the valence band whereas, in the semiconductors which are n type the Fermi level is nearer to the conduction band. This inhibits electrons from n region diffusing in the p region, but when you have a forward bias what happens we have seen that you are reducing the potential and what you basically get that the width of a depletion region decreases.

Therefore, the Fermi level is no more constant and displaced by the magnitude of bias voltage V and this decrease means that the probability of electrons moving from n type to p type becomes higher and the diffusion process is much easier and therefore, the diffusion current is increased and you have the flow of current. And you can just reverse the condition that is in the reverse bias the step function is increasing and hence the probability of electrons moving from n time to p time becomes low and you have the drop in the current. you have already seen that what you have to do? If you want to have a jump from valence band to conduction band, then you must supply energy h nu which is greater than the band gap of the system and then there is a jump of electron from valence band to conduction band. So, when the negative charge reaches the conduction band it leaves behind an effective positive charge which is known as holes. And these electrons can be made to flow through external circuits and if that is possible that means, d q / d t and that= current.

So, you can have photo induced currents. So, what will happen? If you have the photon absorption at the p-n junction, you will find that the electrons will flow from n type to p type and the typical Fermi level would be matching on the both sides. So, the electron hole pairs that are generated within a diffusion length or so, of the depletion layer. may actually contribute to the flow of charge carriers across this junction. So, you must now make sure that the photons which are incident on the depletion layer have energies sufficient enough to break the electron hole pairs which can then be made to move towards the respective potentials. This is the typical way a silicon solar cell therefore, operates you have a p-type, you have the diffusion of pentavalent or trivalent impurity on the semiconductor substrate and then you can convert certain section of the substrate to p-type and then you diffuse another or trivalent depending upon what you want.

If you want an n type you will be diffusing the vapors of the pentavalent impurities and that would lead to the formation of n layer and at the interface you have the depletion layer forming. What you have to make sure that the n layers are quite thin. So, that the rays which fall on the solar cell are able to reach the depletion layer. On the top you have the anti reflecting coating so, that the rays which are falling are not reflected out, but you they are actually absorbed. Then you have the back electron so, that the electrons which are collected from the end layer can be then made to inject in the p layer and you can have the charge neutrality condition once again obtained.

So, this is a typical way you have the structure of a solar cell. you can have these solar cells which can be either thin film solar cells based on silicon, you can have polycrystalline solar cells or you can even have monocrystalline solar cells. And this is a very common site which you see in India nowadays and these are utilizing silicon as the absorbing layer for the rays which are falling on it and that leads to the generation of electrons and you have the photo induced current flow and therefore, you have the photovoltaics. You have seen that the requirement of semiconductors in the field of photovoltaics is known for many decades. you must ask a question why still there is lot of work going on.

Because suppose you do not just use silicon, you use various other types of semiconductors. We and we have talked about various types of nano materials and semiconductors and how the nature of these materials can be tuned as we move from one type of semiconductors to the other. And if you do that what can be achieved? You can actually achieve different types of solar cells and you can make them to operate for different incident wavelengths. So, you can tune the performance of solar cells depending upon the wavelength from which you want the maximum efficiency by changing the band gap of a material. How will you change a band gap of a material? By using the suitable dowel pins which would change the crystal structure or the lattice of the semiconductor material and that is why you have large number of solar cells which have been fabricated and are being fabricated But the operation of the solar cell still is similarly explained in all these generation of solar cells that you have a p-n junction diode which is forming and the light is incident on this depletion layer which leads to the release of electron hole and the flow of electrons is the electricity which we obtain from solar cells.

You can go through these books to get more information about this topic the basics of solar cells and in the next lecture I will explain more about the material aspect of solar cells which are being fabricated in today's world. So, thank you very much for attending lecture number 2 of week 11.