Physics of Functional Materials and Devices

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Lecture – 45, Week 11

Solar Cells – II

Welcome to the third lecture of week 11. Let us continue our discussions on solar cells and how functional materials are driving the next generation solar cells which are being extensively investigated these days and that is the perovskite based solar cells. So, in today's lecture what I will try to do, I will try to give you the various types of solar cells, what are the mathematical formulations to characterize these solar cells, which materials are becoming important for the solar cells with high efficiencies and what is the probable future direction for this technology. If you see that the energy sources are mostly characterized on the thermal energy sources, mechanical energy sources and photovoltaic sources and we will be focusing on photovoltaic. Is it a new technology? You will find that Becquerel actually discovered the photovoltaic effect in 1839. So, just like what we had discussed during the discussion on the energy storage technologies, it is nearly 200 years since the first voltaic pile was designed and fabricated and demonstrated that we have reached today's world.

Lithium-ion batteries are so important. So, similar to that energy storage technology here also you will find that we are talking about a technology which is again what nearly 200 years old. So, after the discovery of photovoltaic effect in 1839, then came the famous work in 1875 by Grylls and Evans, where they used a selenide as the solid material and showed that light can be used to generate electricity. Then for another 20 years work was going on in the field of selenides and then seeing how to improve the efficiencies of these type of materials.

But probably Frits first demonstrated the solar cell concept in 1894 and just started with 1 percent efficiency. The whole concept was actually demonstrated you can have electricity generation if you make the solar light incident on a material that solar cell had just 1 percent efficiency. But a major breakthrough came in 1950s when the team in Bell labs showed that by having doped silicon. that means, you are going from intrinsic type semiconductors to extrinsic type semiconductors and using these types of semiconductors you can go to around 5.7 percent efficiency in a solar cell.

We are in 2023, what are the typical numbers we are quoting? We are still quoting 20 percent, 25 percent what is available in the market may be around 18 percent. So, another 70 years since 1950 and we have improved the performance by what may be 15 percent or 20 percent at most. But if you really look into the impact of improving the efficiency just by 1 percent, you will be amazed to see why there is so much of interest in research activities in the field of solar cells. So, it is a continuous work for more than a century and it continues to be investigated and for coming few decades this will be a major area of research as well as applications of various types of materials in these technologies. In the previous lecture we have already seen that we are probably in the fourth-generation solar cell classifications.

Where we are using perovskite type materials to fabricate these solar cells and these solar cells have efficiencies already of the order of 28 percent or more. You can compare the PV with photoelectric effect and you will be easily able to find out what are the similarities between PV and PE effect. This is the same concept which was described in the previous lecture. So, a quick revision what are we doing? P-V effect we are ensuring that the light falls in the depletion layer of the p-n junction and the recombined electron hole pair is made to separate and because of the intrinsic electric field which is built across the junction electrons move towards the n-type p type attracts the hole and these electrons then are able to flow through the external load. And what you get is the flow of current when you have the electron flow from the n type to the p type region of the p n junction.

The electron flows through the grid electrodes to the back electrodes and you are finally, achieving the condition which is giving you the charge neutrality when the electron from the n-type flows through the external load and gets inserted in the p-type region and this p-type region has a hole which is available and p n junction is driving this separation and flow of electrons towards the n type holes towards the p type. If electrons come to the p type region, then they recombine and you have a charge neutral state. Some of the parameters which are therefore, used to explain the operation of solar cells are you have the short circuit current Isc. This is basically the current which is obtained when you have a short circuit mode between the p and the n types of the solar cell. Then you have the open circuit voltage Voc.

So, you have no external load you just measure the voltage which is developing across the p-n junction. Finally, you have the current that is the solar cell if it is connected through an external load R_L, what is the current which is flowing through it and this current would be having a value which is less than the short circuit current and voltage across the load would be less than the Voc value. this is the current which is useful for us. If you derive the solar cell equation, what are we going to use? We will have two concepts, one the drift current and the second the diffusion current. If you have the diffusion current which is dominating that means, you are in the forward bias, if you have the diffusion current which is actually less than the drift current then what is the condition you are in the reverse bias.

When you want that more light should fall on charges which needs to be separated. In addition to that you also want that more charges or such centers should be available to you that they can be separated out. That means, you should have a much wider depletion layer so, that more number of electron hole pairs are available which are waiting to be broken and separated. So, that you have more electrons flowing towards n type and more holes waiting to move towards the p type. if you want this condition what is the thing which you are looking at? You are basically looking at the condition where your p-n junction should be reverse biased so that you have a wider depletion layer.

If you are looking into the net current which is going to be available when there is an incident photon. What would that current be? That would be

$$I_{net} = [I_{diffusion} - I_{drift} - I_{photon}].$$

That can be rewritten by the values of the I_{drift} and I_{photon} and you will find that the solar cell will be equal to $\{I_{photon} - I_0\, e^{\frac{ev}{KT}} - 1\}$. And we define

$$I_{cell} = -I_{cell}$$

Why? Because the battery delivers a current to an I_{cell} external load that becomes more positive as I_{photon} increases and therefore, you define

$$I_{photon} = \{-I_{net}\}.$$

Both I_{cell} and V are hence the positive quantities.

If you look into the overall performance, this is what you have that from the I-V curve in the first quadrant, you can get the current which is given by

$$I = I_L - I_0 e^{[(\frac{qV}{nkT})-1]},$$

where n is the ideality factor. The term -1 is a factor which can be neglected as the exponential value is much greater than 1 and hence you will find that you can write the values of I as

$$I = I_d - I_L$$

$$\text{Or, } I = I_s e^{[(\frac{qVb}{nkT})-1]},$$

and you have an additional term I_L as the term which is reducing your observed current. So, this would be the typical solar cell plot if you have the I-V characteristic, this is what is happening. The shaded area is the quadrant in which the cell generates electrical power. As the illumination of the cell increases, what will happen? The value of I_{cell} V curve will move to upwards as indicated by the dashed line.

What would be the equivalent circuit? You will have a current source, then you have a voltage, then you have a p n junction and that is giving you I_{cell} and you have the load. So, if you look into the solar cell equation and rewrite everything, you will find that

if V = 0,

the cell current flowing in the external circuit is I_{photon}. If you replace I_{photon} as the short circuit current I_{sc}, then you can get

$$I_{cell} = I_{sc} - I_0 e^{[(\frac{qV}{nkT})-1]}.$$

and this is the solar cell equation. What would be the maximum power delivered by such a solar cell? If you want to have the open circuit solar cell where I cell is equal to 0, you will get

$$(I_{sc} / \text{Io}) + 1 = e^{[(\frac{qV_{oc}}{KT})]}$$

Usually, I_{sc} is much greater than I_o. and therefore,

$$V_{oc} = \frac{KT}{e} \ln \left(\frac{I_{sc}}{I_0}\right)$$

The power delivered by a solar cell is equal to the product of the cell current I cell and cell voltage V. we have already calculated the value of I cell. So, if you want to write the value of,

$$P = V\, I_{sc} - V I_0 \{e^{[(\frac{eV}{KT})]} - 1\}$$

If you plot this as a function of V, you will find that there is a maximum voltage at which you will get the maximum power. On either side of this voltage, you will find that the power drops. For maximum power what should be the condition? You should have,

$$\frac{dp}{dv} = 0.$$

So, you take the differentiation and you will get the equation mentioned here.

If (eV/ kT) is much greater than 1, what will happen? You can write the equation as,

$$I_{sc} - I_0 \{e^{[(\frac{eV}{KT})]}\} \{1 + \frac{eV}{KT}\} = 0.$$

We have already seen what is the value of I_{sc} , substitute that value. What you will get? You will get the relationship between,

$I_0 \{e^{[(\frac{eV_{oc}}{KT})]}\}$ is equal to the term on the right.

Rearrange, when you rearrange what you will get? You will get the value of v and that will give you the value of Vmp. and you know what is the maximum voltage at which you will get the maximum power. Similarly, you will be able to derive the maximum current at which you will get the maximum power.

The ratio of maximum power and the product of $I_{sc}V_{oc}$ is called as the fill factor. In practice, fill factor is approximately 80 percent or higher. The ratio of maximum electrical power to the incident solar power is defined as the power conversion efficiency. So, what you have?

$$\eta = P_{mp}/P_s = \frac{FF.Isc\ Voc}{P_S}.$$

And for commercial solar cells η is approximately 20 percent. These efficiencies are generally measured under AM 1.5 condition as the standard that is you have a measurement at 25 degrees while believing that you have the incident radiation of 100 milliwatt per centimeter square. then you have the solar simulators and you can calculate and find out the performance of the solar cells. Third generation onwards what you saw that you can modify the performance and we said that you can modify this performance of the solar cells for examples by changing the materials.

In a dye sensitized solar cell. So, there would be a dye which would actually be deposited on the semiconductor for example, you have TiO_2 base semiconductor, then you have a die which is deposited on these semiconductors, the die will absorb the light and you will have the whole process taking place. So, what you will have from the electron you will have the HOMO and LUMO levels of the dye. that will lead to the transition of electron from the LUMO level of the dye to the conduction level of the semiconductor and if you have excess electrons here then that can flow through the external load giving you the current. and typically, the values which are being mentioned are nearing to the values of 15 percent or but they have their own disadvantages because the stability issues of these solar cells are quite tricky.

Then you have to talk about the stability toxicity of the electrolytes which are used and then how to replace these electrolytes. So, the linkage issues can also be addressed for that came the knowledge on perovskite solar cells. So, what you have? You have the perovskite as the active material and what you do you then transfer the electrons from the perovskite layer to the semiconducting layers. This is the typical configuration of the perovskite solar cells which are extensively studied. So, if you have metal oxide-based materials, then you have perovskite materials.

What are you going to do? Then you have the hole accepting layers. What are you going to do? You can choose the combinations in such a way that you improve the efficiencies. You already know how to tune the perovskite materials. You can have various dopants

which will change the character of the perovskite material. So, all the knowledge about these perovskites come handy in this solar cell.

Then you also know how to fabricate various types of metal oxides. in addition, you know how to change their band gap as a function of dopant or as a function of particle size. Similarly, for hole accepting layers you will have the knowledge to modulate the band gap of these layers by which they can absorb holes more efficiently. If that is possible then the charge flow would be much higher and you can improve the efficiencies of the solar cells and that is what is happening by choosing the right material the efficiencies of the solar cells are being improved quite significantly to what they were around 5 years back. If what have we seen? initially perovskite was the name given to materials which had ABO_3 type structure, but in solar cells what are we having A is the organic or inorganic cation, B is the inorganic cation, and X is a halide.

So, you have an ABX_3 kind of structures and not ABO_3 type of structures, but overall unit cell is still looking similar to what you had in a perovskite cell. These systems have quite clear advantage over many other systems that have been developed reported you can see that the response characteristics of these materials are quite higher than the CIGS or crystalline silicon or even gallium arsenide-based systems. So, you will have the device configuration what would that look like either you will have a planar configuration or you will have a meso configuration. If you see what would typically be happening you will have an absorption of light by perovskite, then creation of electron hole pairs, then the efficient separation of electrons and holes and collection of electrons and holes at the respective electrodes, then you have the top electrode and the bottom electrode. from where the electrons can come out and then get impinged into the whole transport layer.

It must be very clear to you now. that although this topic is slightly advanced topic, but the concept which are being covered in this course that is materials and the type of materials which have been discussed throughout this course are extremely important and are being routinely used in perovskite based solar cells. They are also used in the dye synthesized solar cells and as you tune these materials further you will reach a condition where the desired efficiency would be obtained and such solar cells would become easily marketable. The major issues with these kinds of solar cells that is perovskite and dye-sensitized organic solar cells are about the stability of the materials, how you want to make them in air Sometimes their fabrication needs slightly more complicated protocols and strategies. You have to work under glove box or in clean rooms which increases the cost of these devices in addition to increasing the carbon footprint of the overall technology.

But the road map is well defined. you need to use functional materials, metal oxides, perovskites or hole transport layers. So, that you have efficiencies which are much higher than what are being achieved. Today once that is done you will find that these next generation solar cells would become commercially viable and become available in the

market. So, to develop more understanding about this lecture or the points mentioned in this lecture, you can go through these references. And from the next lecture we will move to the final module of this course that is the characterization techniques which are important in the field of functional materials and devices. Thank you very much.