Energy Resources and Technology

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Lecture - 17
Photovoltaic Power Generation

Starting today, we will be introducing the subject of the different types of conversion of solar energy namely, photovoltaic energy conversion.

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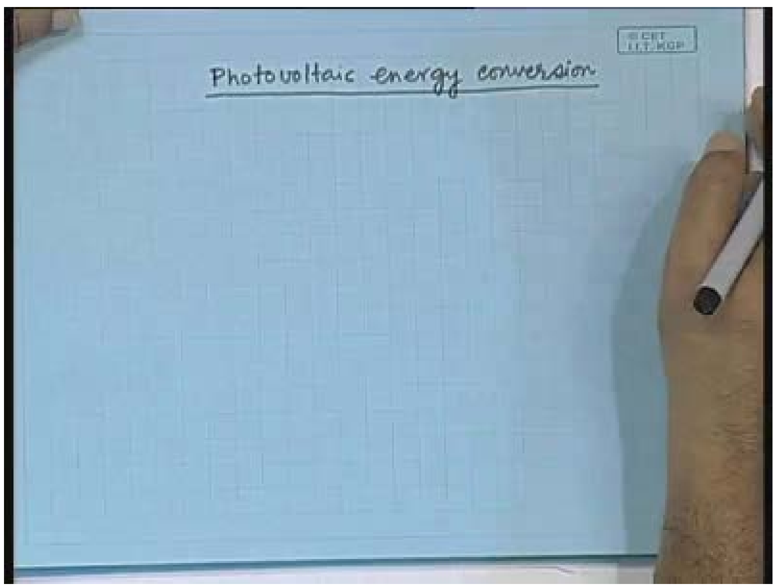

Now, essentially in photovoltaic energy conversion, you seek to convert the solar energy directly into electricity without going through the intermediate stage of converting first into thermal energy and then electrical energy. So, it is a direct conversion of energy from sun's rays into electrical energy. In essence, it works on the principle of a simple PN junction about which I suppose you have all learnt. So, I will not go into the essential details of that, because I will be assuming that you and any engineering student who attends this course would be knowing. So, what is the essential point? In any semiconductor material say silicon, if you dope it with certain things, then the balance of electrons and hole changes. If you dope it as P-type, then you have excess of holes. If you have, if you dope it with N-type, you have excess of electrons and what is the thing you dope with for P type, for P type?

Student: …

Phosphorus and …, yes and for N-type, no, no; there is another semiconductor? You have forgotten, does not matter. Initially, let us start with just assuming that we have got a P-type semiconductor and N-type semiconductor and those details of how to dope and stuff like that, we will come later. Now, if you have a P-type semiconducting material or N-type semiconducting material, as you know that in a semiconductor, we can identify a band gap between the conduction band and the valence band.

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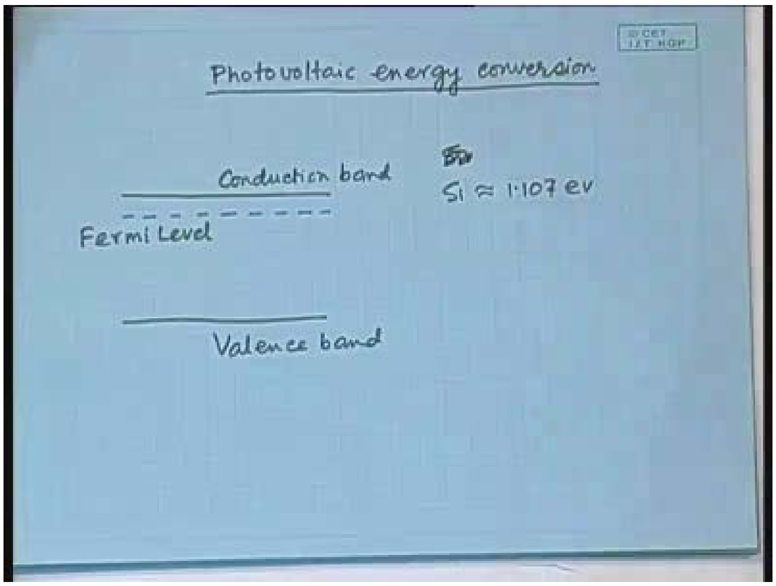

So, normally this would be depicted as one band for the conduction, another band for the valence and the band gap for the case of silicon is about 1.107 electron volts; for silicon it would be 1.107 ev; so, this band gap. Electrons, when they are in the conduction band they are conducting. Holes, when they are in the valence band, they are conducting and the average energy of the electrons would be given by a level called the fermi level. So, the fermi level would be a level in between these two and in case of the P-type semiconductor, the fermi level will be closer to the valence band. In case of the N-type semiconductor, it will be closer to the conduction band, right. That was the basic semiconductor theory that you have all learnt, clear. So, there would be a level say, in case of an N-type semiconductor somewhere here that will represent a fermi level. So, this is the conduction band and this is the valence band and this is the fermi level representing the average energy of the electron in that material.

Now, when you join a P-type material and the N-type material to produce a PN junction, what happens, that also you have learnt. The fermi levels become equal and as a result the band bends like so.

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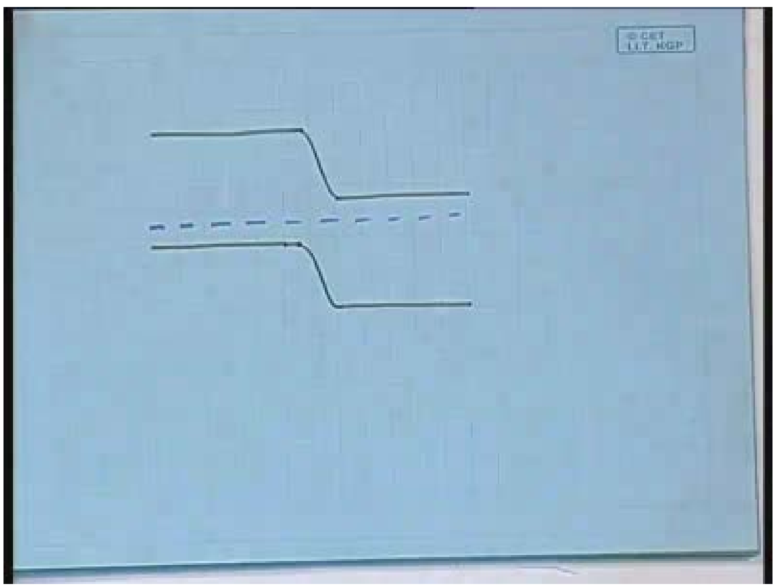

The fermi level becomes equal and if in this side it is a P, then the valence band is somewhere here and the conduction band is somewhere here and in this side if it is N, then the conduction band is somewhere here and the valence band is somewhere here and so, there is a band bending, right. So, this is the basic theory of PN junction you have learnt. Because of the band bending, the electrons find it difficult to go up the hill, holes find it difficult to go down the hill and therefore, electrons flow this way and the holes flow this way is effectively blocked and therefore, it acts as a diode, right. So, that is the basic theory that you have already learnt.

In case of the photovoltaic cell, we essentially use this property, but in addition to that what is not there in the normal diode is that light is falling to a place, where? Very close to this band bending region; as a result, as the light is incident upon the material, the electrons will absorb the photons and if the photon energy is bigger than the band gap energy, then an electron hole pair is created. Electrons are knocked off from their positions to make them free. As a result, you have an electron going to the conduction band and a hole, naturally when electron is knocked off, it leaves behind a hole, so hole goes to the valence band. So, in other words, it results in the creation of an electron hole pair.

Now, imagine what will happen if an electron hole pair is created somewhere here?

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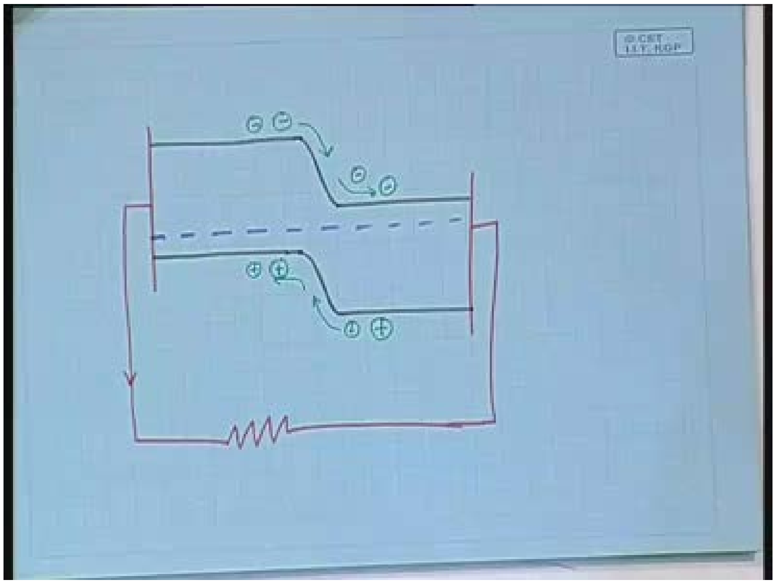

So, electron hole pairs are created and imagine that one electron hole pair is created somewhere here. Do you understand why the electron hole pair was created? Essentially, if the light has energy bigger than the band gap energy, then it knocks an electron off its site in a particular atom, makes it freely moveable in the bulk material. As a result, the electron goes to the conduction band, leaves behind a hole which is also free to move that is in the valence band. So, suppose it has been created here, now electrons have the natural tendency of flowing down hill, so it will naturally go like this.

Supposing more electrons are created somewhere here and holes have been created somewhere here, then the electrons from this side will flow down the hill and holes tend to bubble up. They behave like bubbles in water that means they tend to flow up. So, the holes will flow like so. As a result, there will be a larger concentration of holes in this side and a larger concentration of electrons in this side, thereby producing a voltage difference and if you, if you put some kind of a charge collector in the two sides and connect by means of a resistance, then the charge flows continuously and you have the flow of a current.

What will be the currents direction?

Students: …

No; outside, it should be like this. So, this is the essential theory behind the photovoltaic cell. So, unlike the normal PN junction and diode that you have come across what additionally is here? The creation of the electron hole pair and the electron hole pair has to be created close to the bending region which means that a large number of, large amount of area has to be exposed to sunlight and the whole PN junction has to be over that area which means imagine that you have got the thing like this, on which the light falls.

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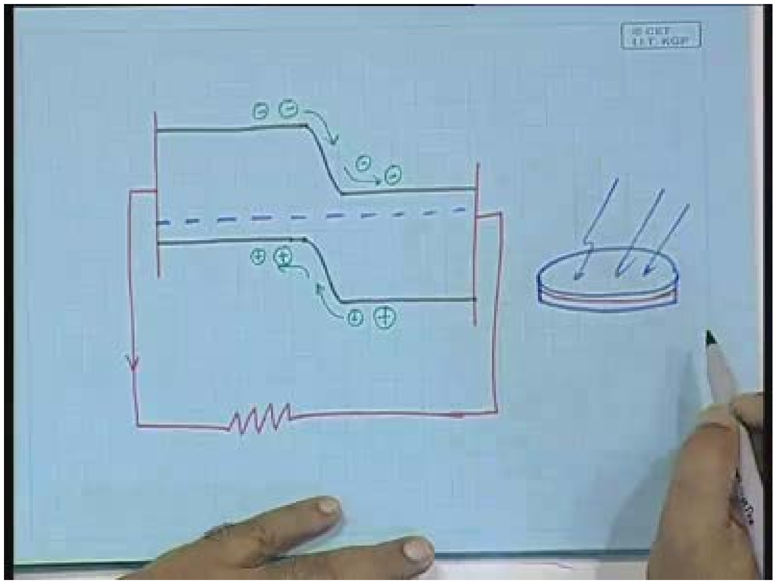

The whole thing has to be the PN junction, the whole thing. So, you might imagine that here I will just blow up by means of a larger thing. The P N junction might be somewhere here. That means the PN junction has to be over the whole surface which is the extended surface. So, how to make such a thing? I will come to the production process per say a little later, but essential structure is that below it there has to be some kind of a metal substrate, metal substrate in the sense that you have to collect the charge. So, there has to be metal contact and that metal contact is in the form of, if I, if I draw the side view, it will be something like this.

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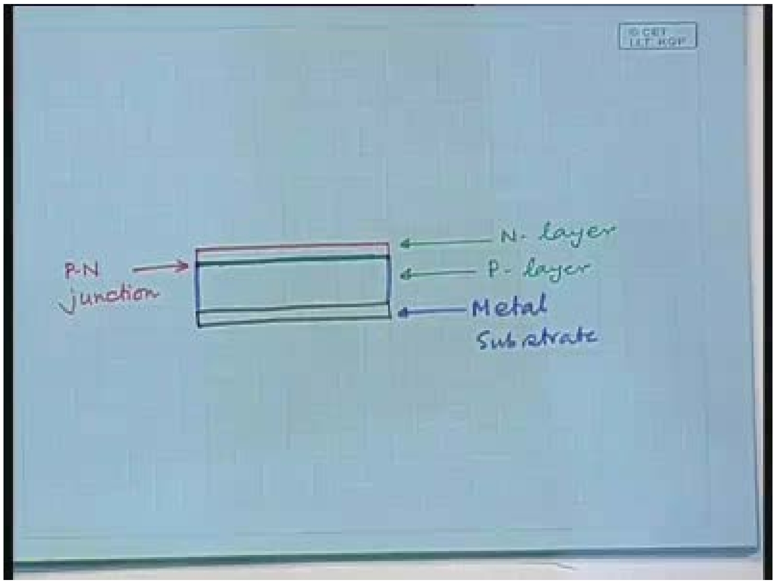

First, there is a metal substrate. Then, you have a reasonably large layer of P, then you have a smaller layer of N and here is your PN junction. So, light falls on the top surface and the depth of the N layer is made such that the light penetrates up to the junction level. So, it is actually very thin layer, very thin layer. It is not, not a thick layer. It is not that you take some N and you take another, take some P, take another N and just put it like this; no, it is not like that. It is grown in a different way; I will come to that later. So, here is the metal substrate, here is the P layer and here is the N layer and this fellow is the PN junction, but there has to be some way of collecting the charge there.

At the bottom side, collecting the charge is no problem, because you already have a metal contact. But at the top, you only have a P-type semiconductor layer. There has to be some way of collecting the charge. So, the way to collect the charge is to lay a grid of metal. The more extensive the grid, the more will be the blocking of the sunlight, remember. So, you have to allow certain, certain maximum amount of sunlight to pass through. So, it is not really covering the whole surface, rather it is like a metal, a collection of metal fingers that are laid on the surface which collects the charge from the top level and then it is connected to, with, by means of some kind of a load to the bottom, to the bottom level.

So, that is the structure of the PN junction, structure of the photovoltaic cell. The manufacturing process and other things I will come to a little later.

Now, what are these made of? In general, these are made of silicon. In general, as yet whatever photovoltaic cells you see in India, they are all made of silicon, but then there are a few things that you need to understand carefully. First thing is that the PN junction being here, the electron hole pair is created all right and they go to different directions all right, but before they are collected by the contacts, they may also recombine. Normally, they may also recombine. As a result, the current generation will be less, current generation will be less. So, in order to avoid that we need to ensure that there is minimum recombination. Now, it so happens that if there is any deformity in the lattice structure, these act as recombination centers.

For example, if it is single crystal that means all the silicons are arranged in a nice array, then obviously there is no deformity and nothing acts as a recombination center. But, if there is a crystal here, another crystal there, in between there is a crystal contact, then there are dangling bonds, bonds that are unsatisfied and these dangling or unsatisfied bonds act as a recombination center. So, it follows immediately that it is desirable to have a single crystal of silicon to make the photovoltaic cell. In fact, almost all the, almost all the photovoltaic cells that are commercially manufactured in India are single crystalline sources, but also it is a fact that there is a great expenditure in making the single crystal and therefore, some companies prefer to make it cheaper by sacrificing some amount of efficiency. In that case, they use what are known as the polycrystalline silicon solar cells.

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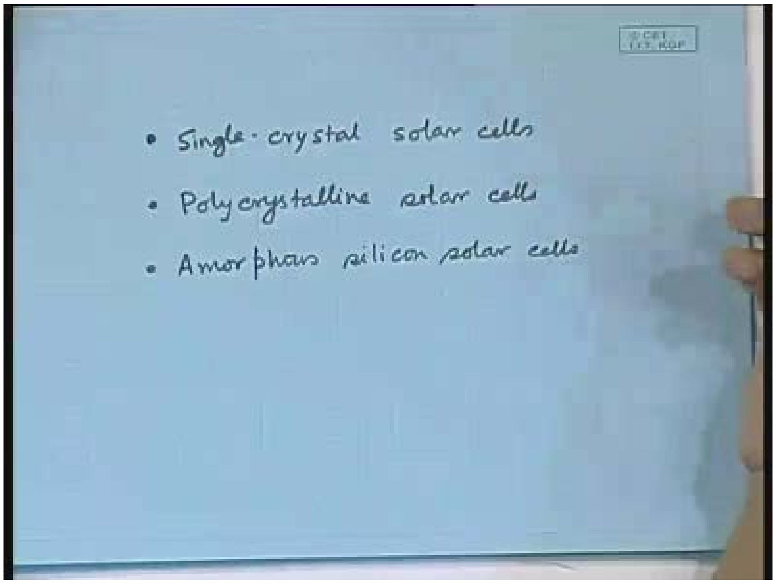

So, we can now enumerate, enumerate a few possibilities. Number 1, the single crystal, polycrystalline and polycrystalline means that is a crystal structure, but the whole thing is not made of one single crystal. So, that is the polycrystalline solar cells. For example in India, the Tata BP solar, that company manufactures the polycrystalline solar cells, while BHEL, CEL and companies like that produce single crystalline solar cells. There is another type of solar cell, where, in order to make it cheap, very cheap you do not make a crystalline structure at all. These are called the amorphous silicon solar cells. Obviously, their efficiency is very low, but the cost of production is also very low.

For example, in calculators you will find a small, some calculators have small solar cells, right. These are all amorphous silicon solar cells, because there the amount of power necessary is very small. So, they simply put some amorphous silicon solar cells. So, there are three types. Amorphous silicon solar cells are really considered for bulk power generation. They are considered for that kind of specialized power generation, where the power requirement is small, but at the same time, you have to remember that amorphous silicon solar cells are very cheap to manufacture and moreover, there it is possible to make thin films. So, a thin film laid on something can also work as solar cell. So, that can be possible with amorphous silicon, which is not possible with single crystal, because that is hard, single crystal.

Now, you might ask that while talking about conversion of one form of energy to another, we had talked about the quality of energy, right, in the beginning of the course, quality of energy. Electricity is obviously high quality energy. What is solar energy? Is it high quality or low quality? Low quality; so, by the law of thermodynamics, there has to be some kind of a limit, there must be some kind of a limit. So, it is not possible to have 100% conversion of solar energy to electrical energy.

What could be the sources of the inefficiencies? One, what, combination?

Student: Recombination.

Recombination is one; that means after the electrons and holes separate, they recombine. That recombination is one source, but before that, let us start from the start. What about the electron hole pair generation itself? When it comes to generation, will it be 100% efficient? No; not because, see in the solar spectrum, there would be some wavelengths that contain energies that are lesser than the band gap energy. If it is lesser, they will not be able to knock off the electrons of their site and therefore, they will not be able to create an electron hole pair. There will be some frequencies that are above, that contain energy above the band gap energy. So, if something has energy that is say 1.5 times the band gap energy, only the band gap energy is necessary in order to create the electron hole pair. Where does the rest of the energy go?

Students: Kinetic energy.

Not kinetic energy, no, not kinetic energy; they are simply wasted as heat. Kinetic energy, the question is there for photoelectric effect. The photoelectric effect is where you have got a metal surface, light shines and electrons are knocked off, of the surface. They go into the surrounding air. This is not what we are considering here. We are considering the situation where the electrons stay in the bulk material. Only they are knocked off their site, so that they become free to move in the material. So, naturally the energy that these electrons absorb in order to go from the, in order for the creation of the electron hole pair is exactly equal to the band gap energy. That is what is needed. The excess energy goes as heat. So, if the light has energy, the specific photons have energy less than the band gap energy, then that is also wasted as heat. If that is above, that is also wasted as heat. That is why it is necessary to choose a material that has the proper band gap for the solar light and silicon is reasonably good.

There are other materials that are being considered now. For example germanium, for example other materials like cadmium sulphide, copper sulphide, that kind of material. But nevertheless, at the introductory level, if you know that most of the solar cells that are produced are made of silicon, which have band gap of about 1.107 electron volts. So, we now understand in what way the laws of thermodynamics works. Now, in the solar cell, then we have to come to the idea of how to make the single crystal solar cell, because that is the most predominant. Single crystal solar cells obviously have the largest efficiency. Normally, the efficiency would be of the order of say 20 to 25%. There have been good, well manufactured solar cells reported with efficiencies of the order of 27 to 28%, but the run of the mill standard, industrially produced solar cells would have efficiency between 20 to 25%. If it, if it comes below that, they will know that that cell is bad. That is it.

Now, the efficiency of the polycrystalline solar cell would be of the order of 10% to 15% and the efficiency of the amorphous silicon solar cells would be of the, of the order of 3% to 5%. So, this is very less efficient, this is medium and this is, this is reasonably high efficiency.

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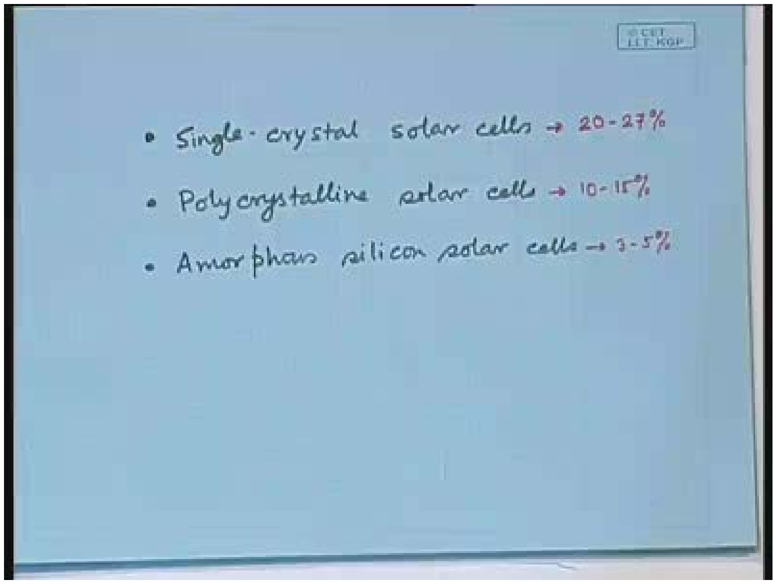

So, if say, here the efficiency is somewhere between 20 to 27% and here the efficiency is say 10 to 15% and here the efficiency is 3 to 5%, so naturally we need to understand how to make these and that should tell you how the solar cells are actually manufactured.

Now, in solar cell manufacture, the essential raw material is what is known as solar grade silicon. The solar grade silicon means that from the SiO 2 or quartz steel, ah, quartz sand, by means of reduction process, first silicon is produced. Now, that silicon contains many impurities and for various different purposes, you need to remove the impurities to different extents. Highly refined silicon would be needed for the highly refined kind of activity like production of VLSI chips and stuff like that. Obviously, for solar cell production, you do not need that kind of refinement; you do not need that kind of refinement. So, what is normally done is some amount of impurities can be allowed, thereby reducing the production cost.

Ultimately, when the basic material is produced, then you have to, you have to make somehow a single crystal. This is done by first taking a crucible, heating it up so that it melts. So, there is a molten material and you have to add a seed in order to, in order to start the formation of a crystal. So, there is a metal contact. At the bottom of it, there is a, there is a silicon seed which is just touching the surface of the silicon, molten silicon, right. Now, it is cooled very, very slowly, so that only the surface, close to the surface it becomes slightly lesser than the melting temperature, so that the silicon starts to solidify. As it solidifies and gets in touch with that seed, it settles there and as a result, the crystal starts to grow. As it starts to grow, this metal holder is pulled up slowly, very slowly. As it is pulled up, at the contact more and more metal will be formed, more and more silicon crystal will be formed and you ultimately pull it up and what do you produce? A cylinder, a cylinder of silicon, right; so, that is why the silicon, these things are called ingots. The silicon ingots are produced which are always of a circular cross section. Due to very natural reasons, you cannot really make square or something like that, because you are naturally pulling it up and it is taking the shape on its own accord and it will automatically take the shape of a circular, so you pull up a cylinder.

Now, this cylinder up to this as yet India does not have a facility of making it. Though we are now installing such facilities, but as yet, as yet these ingots are imported. Then what is done? Then these ingots that means you have got a silicon structure, these are cut. So, first there is a machining process by which it should be cut into slices. So, you get very thin about 1 millimeter thick slices, each of which will produce a solar cell. So, that is why the solar cells are circular in shape, circular in cross section. After these are put, the bottom metal contact is first laid. So, one 1 meter thick, about this much circular cross section slice is taken and the bottom contact is first put. The bottom contact is often made by means of first making a paste of powdered metal and then painting the bottom that way, simply and then when it dries off, you have got a metal contact.

Now, you have got the material; oh, by the way, the material that is produced is essentially P-type material. That means when the ingot is produced, it is already P-type. It is not just raw silicon, already it is doped. So, you have got a P-type material. Now, you have got the bottom contact, you have got P metal.

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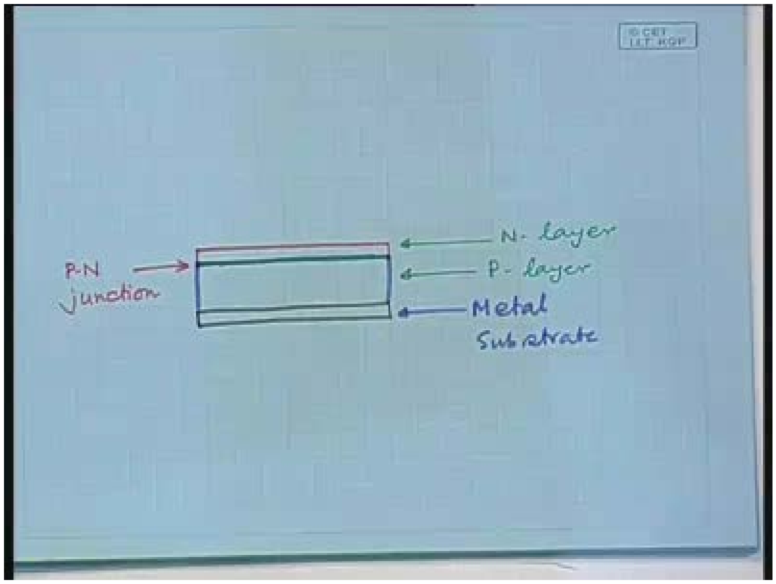

Now, this is taken inside a chamber in which phosphorus vapour is put in. This is heated to a particular temperature, so that the phosphorous vapour goes into the material, thereby creating a layer of N and the time of exposure, the amount of vapor that you put in, that decides to what depth it will go. That is why, these has to be very precisely controlled, because this, if the PN junction is formed much below at a greater depth, then the light will not penetrate up to that point. Naturally, the electron hole pair will be created somewhere here, not here. If that happens, then obviously the flow of electron, the electrons separation will not take place.

So, in order for the electron hole separation to take place efficiently, the electron hole pair has to be created very close to the junction. For any material you know the penetration depth. So, you have to exactly make the arrangement in that chamber, so that the PN junction is produced only to that depth. So, that way you produce a layer of N. Now, the top layer is left. Top layer means the metal fingers, have you ever seen the screen printing process, screen printing by which your marriage cards are printed? If you feel the marriage cards, you will find that it is a bit, you know, elevated. You can feel with your hand. Do you know how it is done? You need to wait till you get married to know how it is done, right?

It is done by this, by the very simple means of a silk screen. There is a frame in which there is a silk screen. Now, people make masks. You can also make mask simply by using some kind of glue and painting over. The part which is masked will not allow the colour or the paint to go in. The parts that are not masked will allow the paint to go in. So, some parts of it are masked. You might also mask simply with the help of a bit of cello tape, so certain places are masked and then they take the paint on a roller. They simply take the paint on a roller and press it. As a result, the paint goes through the silk and attaches to the paper that is placed below. So, they place the paper, the silk screen and then take the paint with a roller and then press it. That is how the impression is made.

Nowadays, you have got very refined process of making the mask, so that you type something in a computer and that automatically goes, it goes, produces a mask, so that you do not have to really do it by means of cello tape or by hand painting the mask. There are ways of doing it automatically, but nevertheless the essential process is that you have the mask, the mask does not allow the paint to go in. The place where it is not masked that is, that is the place where the paint goes in and finally that is what you see on the paper. That is how it is made and that is how, since the paint is bulk paint, you have a slight bit of elevation there. You can feel with your finger that there is a material there.

The top contact of a silicon solar cell is put by exactly the same method, silk screen painting, where again the metal is powdered, very thin powder and made into a paste. You make a similar kind of mask on a silk screen and then that powdered metal paste is painted on to that, as a result of which it goes in and sticks to the upper N layer, where it is not masked and that is how the metal fingers are put, clear. So, metal fingers are put and then that is removed, …., dried and finally, you have the whole thing ready. All these individual ones are connected in series in order to produce a whole panel. Each individual cell will be producing a voltage of the order of 0.8 volts, which is not sufficient for any practical purpose. So, many of them are put in series to produce a voltage something like say, 30 volts which is a useful voltage and that is how the solar panels are made.

Now, let us come to another issue. The kind of supplies that you have learnt of, for example, the supply in the socket, what kind of source is it? It is a voltage source, right. So, what is the character of the voltage source? It is that the voltage remains constant irrespective of the amount of current you draw. The current you draw depends on the load, the load that you connect, whether you connect a heater or a bulb or a fan, depending on that the current changes, but the voltage remains constant. That is why it is a voltage source. Now, notice what is happening here?

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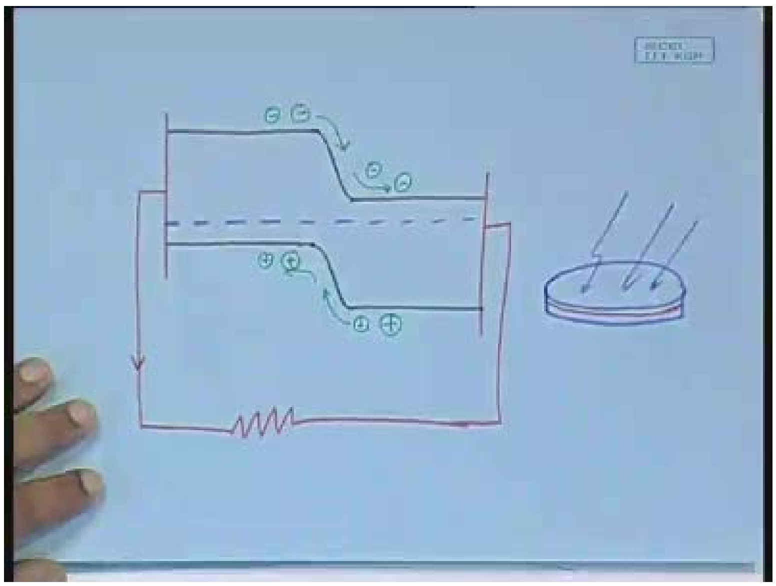

You have got, you have got the solar light coming in and the separation of the charges. Separation of charges means what? Charges flowing in the opposite direction means what? It is not voltage, it is current. So, the incident solar radiation produces the current, so it becomes effectively current source, not a voltage source. It becomes effectively a current source, not a voltage source. So, effectively you have, depending on the amount of solar radiation received, a current source.

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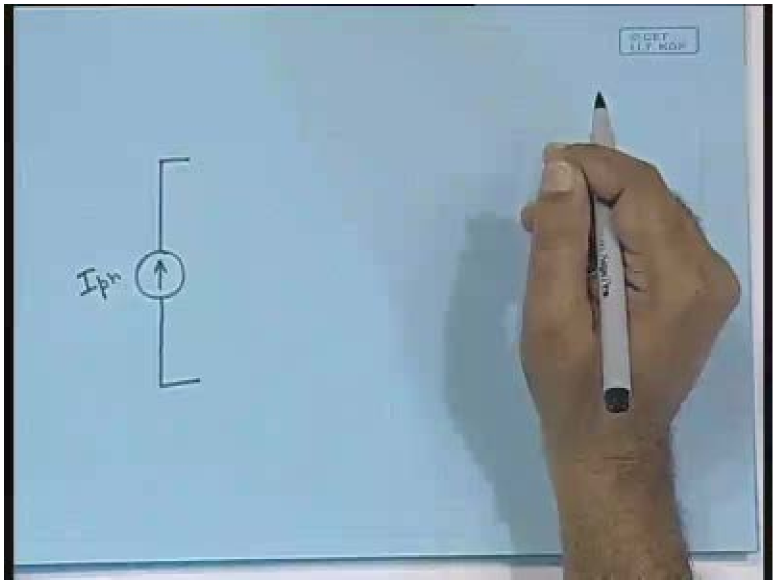

So, if you want to produce some kind of an equivalent circuit, you would say that I have a current source. The current sources quantity, the current is actually dependent on the amount of solar radiation received. So, this is called the photocurrent or photocurrent, I ph.

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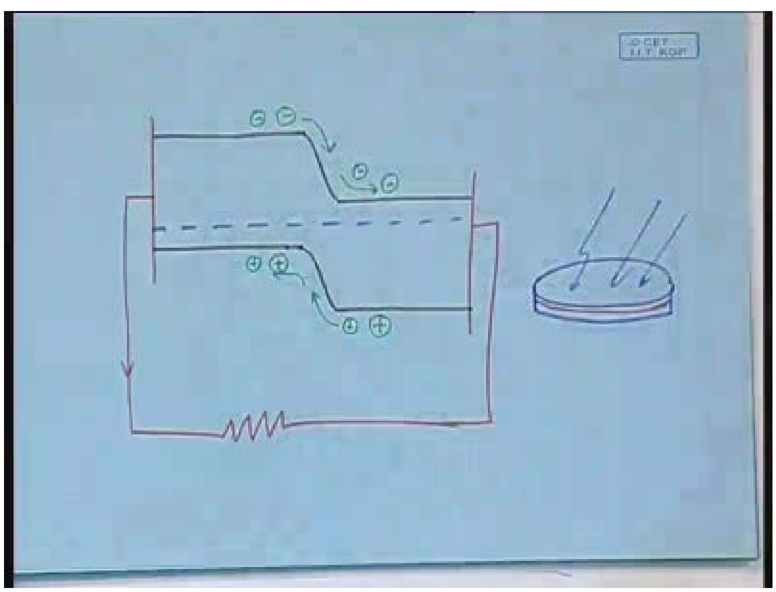

So, one thing to remember, very important, most people do not understand it properly; that is there is a fundamental distinction between the photovoltaic source and any other normal type of source that you, that you come across in everyday life. The ones that you come across in everyday life are voltage sources, while the photovoltaic source is a current source. Now what happens? You have got after all the PN junction and the PN junction implies that it is a diode. So, what will happen if say, you do not connect anything? If you do not connect anything, then there will be a voltage difference and the voltage difference will produce a current through the diode, a forward biased current through the diode. See, it is a PN junction where this is positive, this is negative; it is forward biased. It is a forward biased current through the diode, as a result of which if you connect nothing at the output side, there will be the current generation and the current will be shorted through the diode.

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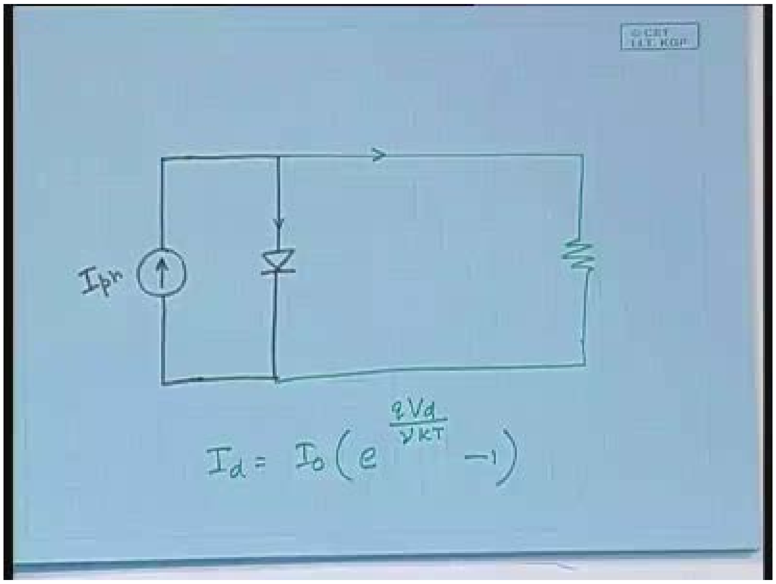

So, this will be like, like so, because this is a PN junction, this is a diode, here is the generation of light which would be shorted through the diode if there is no connection to the external world. Now, if there is a connection to the external world, what happens? There is current flow all right, as a result of which the open circuit voltage that was there, which if it is not connected, then there will be some voltage which allows the full current to be shorted through, but if there is an external voltage, then this voltage will reduce, but nevertheless there will be a voltage due to which there will be a current. So, this diode will remain, but then you have to connect some external stuff here. So, suppose I connect some external stuff, I will do it with a different color with a purpose.

The moment I do this, there will be a current flow. There will be a current flow, some voltage will appear here. This voltage will seen by the diode and the current through the diode will be that due to that voltage and you know how much is the current through the diode. The diode current I d is I naught e to the power the diode voltage, so the diode voltage divided by a factor. Yes? So, no, no, no, no; here it is the electrons charge q, right minus 1. So, this contains all the constants and this is the variable quantity. Which is the voltage here? So, this current will still keep on flowing and the rest of the current will go through the load, right. The rest of the current will go through the load.

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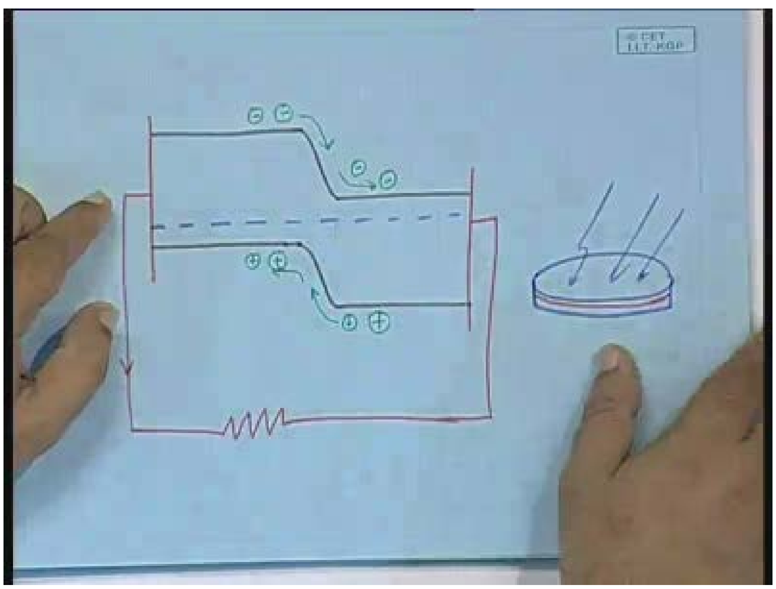

Now, it is not difficult to see that there would be a resistance encountered in the passage of these electrons through the bulk material and the passage of the holes through the bulk material. So, the current passage here will encounter a resistance as it goes from here to here. That resistance will have to be taken into account. Where does it appear? It appears in series with the load.

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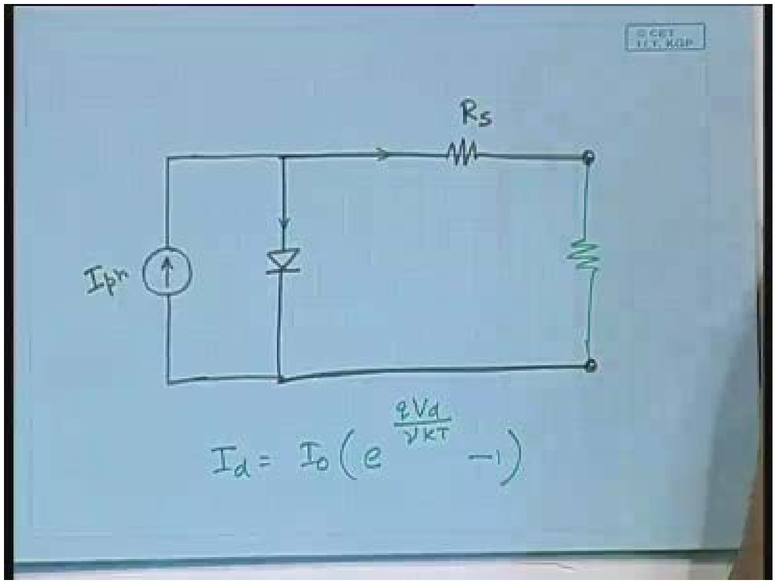

So, that will be represented by means of a series resistance here. So, that will be called the series resistance R s. So, what is the series resistance? That is the resistance of the bulk material. Not only that that is the resistance between the bulk material to the metal contacts, they will also be taken into account, they will also come into picture in the R s. So, R s is a combination of all the resistances that the electrons flow through that solar cell encounters.

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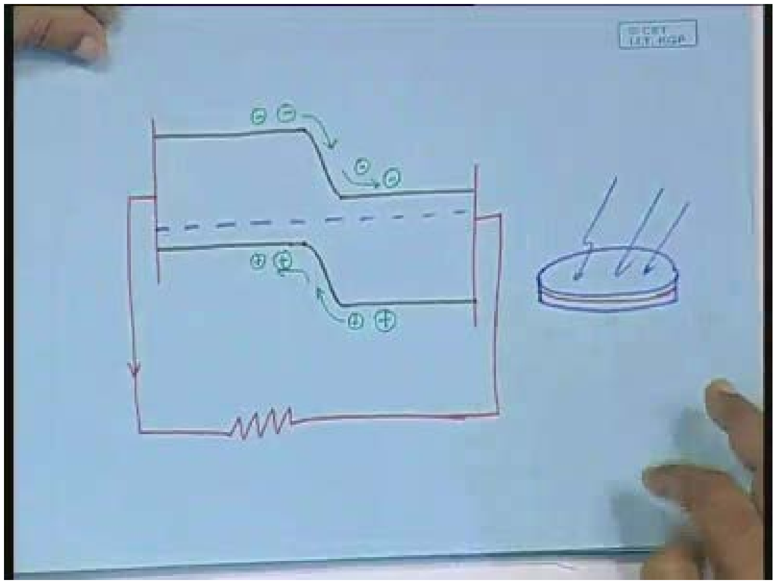

In addition to that, there will be a, you also have to consider the phenomenon of recombination. That means the electron hole pairs gets separated all right, but before they are ultimately separated and flows through the external load, they recombine inside. Now, that recombination somehow has to be taken into account, because the photocurrent that was produced accounted for the whole amount of electron hole pair generation. But, out of that, if a part recombines before going into the load, then that has to be taken into account inside the model of the photovoltaic cell.

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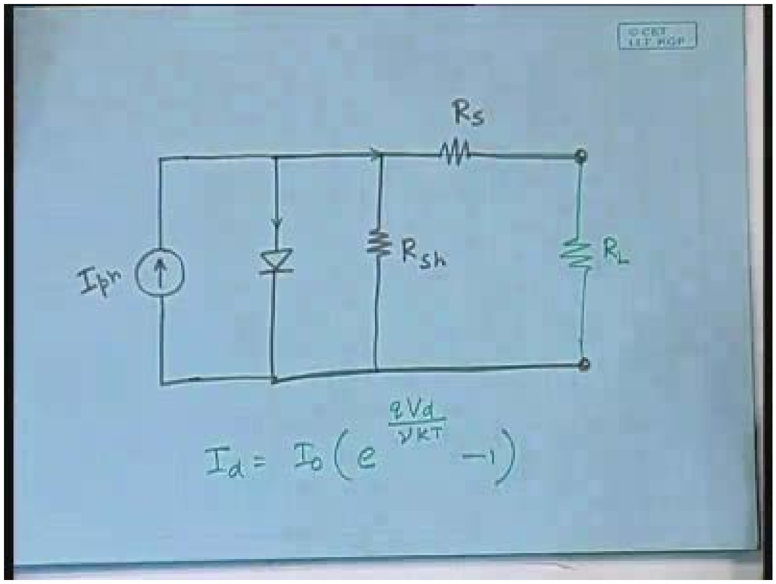

So, where will that be? It will definitely not be in the change in the I ph, because I ph is related to, exactly related to the amount of photons that are received, amount of solar radiation that is received. Now, if there is more recombination, obviously it is not fault of the solar radiation. So, that will not be reflected here. It produces the same amount of electron hole pair generation depending on the energy content of the solar radiation. Will it be reflected here? No, because it is the character the diode. So, it will not be reflected here. But after that, a part of it, part of the current that goes here, does not go to the load. It is somewhat shorted through, shunted. So, naturally the way it has to be represented is by means of a shunt resistance here, R sh. So, what does R sh actually represent? It represents the recombination of the electron hole pair before it reaches the load. So, here you have the simple equivalent circuit model of the photovoltaic cell and this is the load.

Now, let us see, can we now make, produce a relationship between the voltage and the current that are seen by the load? Obviously, we can. Now, let us see, have you, have you drawn this? From this, because I will not be able to display this and the next page together, you look at the circuit diagram and from there, see first let us consider that, first that the R sh is not there. First, let us ignore for the sake of simplicity, we will put it, put that in later, for the sake of simplicity let us ignore the R sh first. So, it is only this part.

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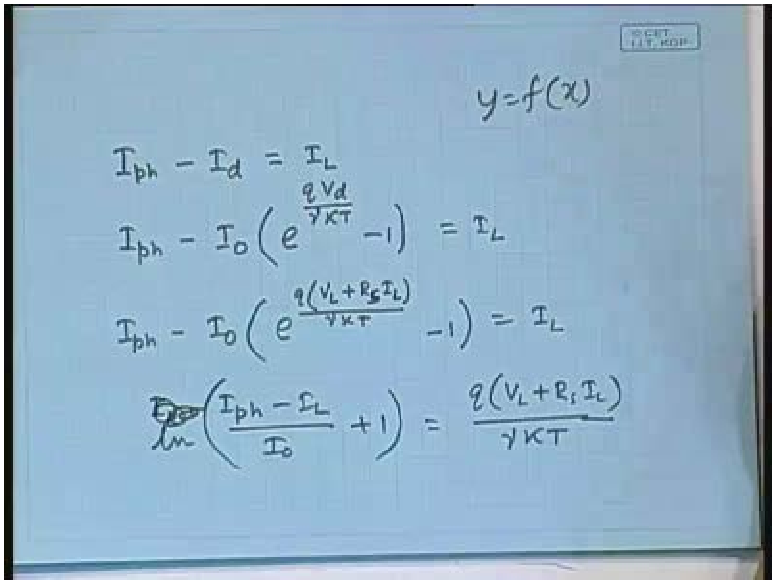

Then, you have the equation as I ph minus I d is equal to I L, I ph minus I d equal to I L, load current, all right, fine, which means I ph minus I naught e to the power q V d by gamma K T minus 1 is equal to I L. This has already produced a relationship between this and that, so let us see. Now, the V d, V d is V L that is the terminal voltage, load voltage plus yes, so here we need to substitute I ph minus I naught e to the power, no, wait, q here, we will substitute what will it be? V L plus I RL I R s R s I L by gamma KT minus 1 is equal to I L, all right.

By the way, I did not talk about the components here. Here q is the electrons charge, d is the diode voltage, gamma is a constant, sort of a curve fitting constant; for different diodes, it will have different values varying between 1 and 3 generally, K is Boltzmann constant, T is absolute temperature, right. So, remember that sometimes in calculation, you substitute this for centigrade temperature; it is not, it is absolute temperature. So, you have this equation. You can see that this already has V L and I L and therefore, this gives the relationship between the voltage and the current as seen by the load. But, this is a hopelessly intertwined thing, right. Will you be able to plot the curve? If so, how will you do that? By MATLAB? You have to tell MATLAB how to solve it, because you see, a curve means y is equal to f x; right hand side should not be, should not have y, right. Here you see they are mixed up. Yeah, you need to solve it by Newton-Raphson method. So, for every value of V, you solve by Newton-Raphson method for the value of I L and then you have to plot the graph. Got it, how to do it?

Now, let us, after we have done this, let us make it more, can we get V L out of it? Can we get V L out of it? Can you just manipulate this to get V L? I think that will be doable; I think that will be doable. So, you have I L minus I ph or I should say I ph minus I L that is better minus I L divided by I naught plus 1 ln is equal to this fellow, right. Now, naturally it is possible to extract V L. So, put this thing down. Now, you can write it, how do you do it?

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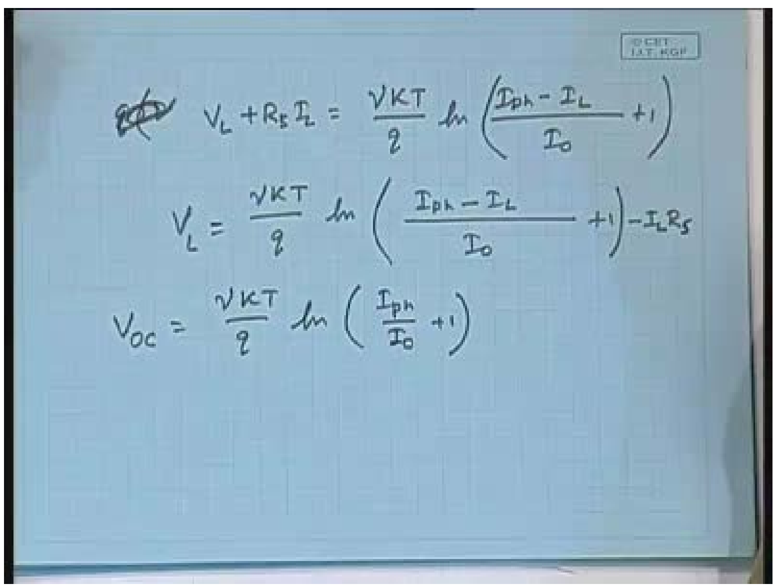

q V, okay, so, let me write in this way, V L plus R s I L is equal to gamma KT by q ln I ph minus I L by I naught plus 1. So, V L equal to this minus I L R s, fine. So, we have been able to extract the V L in terms of I L. This has been possible only because we have ignored the shunt resistance. Once we ignored, once we take into account we will not able be to do that. But nevertheless, that is how we get some, some bit of idea about it. Now, you notice that if we keep it open circuited, I L is zero. If I L is zero and this I L is zero, then you have an expression for V oc, open circuit, as gamma KT by q ln I ph by I naught plus 1. Teek hai?

These fellows are all constants. I naught is a constant, I ph is variable dependent on solar energy and solar energy really changes all over the day. There may be cloudy sky, there may be open sky, there may be slanted radiation coming, so I ph is variable. But, you would notice that the open circuit voltage is logarithmically dependent on the I ph, ln. As a result, even though the photocurrent may become half because there can be cloud, the open circuit voltage will not reduce as much. That immediately gives that conclusion that the open circuit voltage will not reduce as much. Now, I will leave it to you.

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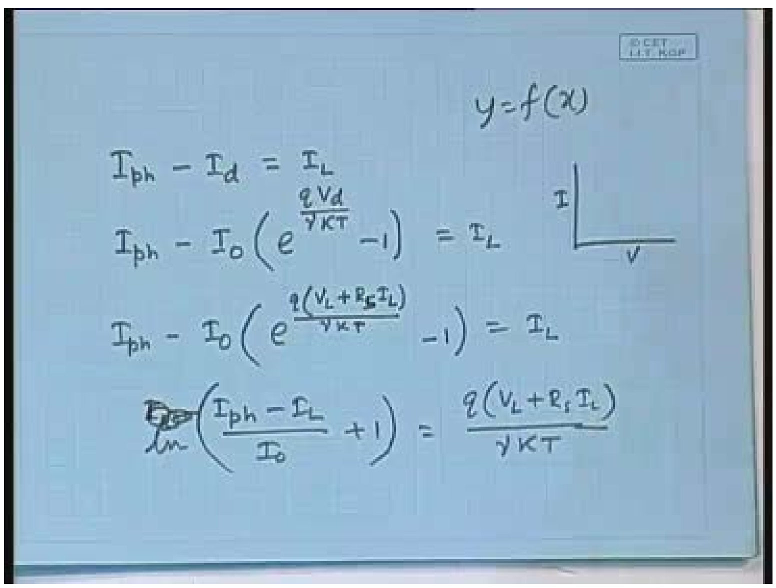

You write similar expressions like this using the shunt resistance. Then, you can solve it by Newton-Raphson, plot the graph. Only thing is that you will know these values; q you know, gamma, take a value between 1 and 3, even 1, no problem, K, you know Boltzmann constant, T, a normal temperature; these are known things, all right. What will be the order of magnitude of I naught? Minus 5, 10 to the power of minus 5 kind of order, right. I naught, what kind of order, order of magnitude have you seen? 10 to the power of minus 5. Okay, okay; you can, you can take values like that. Though, in case of photovoltaic cells, because the structure is different, it has a bit of different values. But, if you are used to that kind of values, take, no problem. Because you have done problems using PN junctions, so whatever values you take, take. But in case of the photovoltaic panel, it will be slightly more than that, anyway. So, you solve. You can solve and you can obtain the characteristic graph plotted with V in the x axis and I in the y axis. On that basis we will talk in the next class. Thank you.

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Instrument to measure the solar incidence, solar radiation. As you can see, there is a place through which the solar radiation comes, something that you can possibly shade and if you shade, then you can get only the diffused solar radiation; if you do not shade, you get the direct solar radiation and the voltage produced is sensed by a standard voltage meter, voltmeter. In this case, we are doing it with a digital multimeter and the voltage and its proportionality to the actual incident solar radiation is given in form of a calibration chart. So, we read out the voltage and from there we can find out the actual incidence solar radiation by referring to the chart.

So, when we try to find out the efficiency of any solar collector, the incident energy has to be found out by, through the pyranometer reading and the energy that is gained is to be found out from the temperature difference between the inlet side and the outlet side and the flow rate. The flow rate can be measured either by a flow meter or simply by collecting the water in a, in some, some kind of container over a given period of time and then measuring it with a simple measuring cylinder.