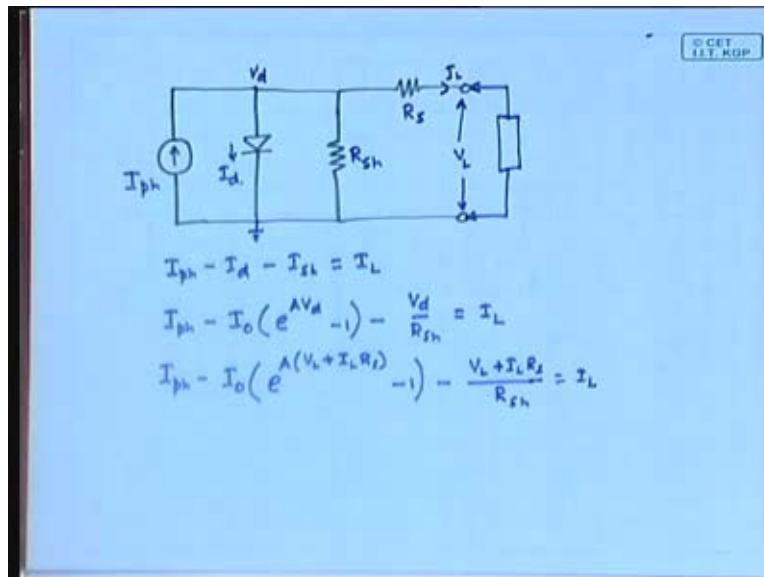


**Energy Resources and Technology**  
**Prof. S. Banerjee**  
**Department of Communication Engineering**  
**Indian Institute of Technology - Kharagpur**

**Lecture - 20**  
**Photovoltaic Power Generation (Contd...)**

Let us first recapitulate. Today we are recording it. Let us first recapitulate where we were.

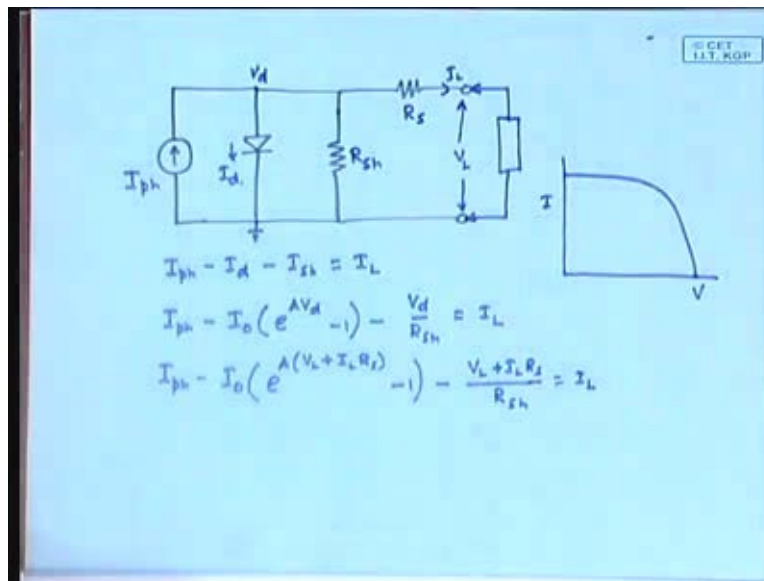
(Refer Slide Time: 1:02)



We saw that the equivalent circuit of a solar cell is where you have a current source connected in parallel to a diode that is forward biased, connected in parallel, who is talking? So, you have these elements. This is  $R_{sh}$  and  $R_s$  and here you are connecting the, whatever the load is and we have seen that the basic equation of this one can be written as, here is the photocurrent  $I_{ph}$  and here is the diode current. So,  $I_{ph}$  minus  $I_d$  minus  $I_{sh}$ , this one, equal to the load current, essential circuit equation and if you expand it, it takes the form  $I_{ph}$  minus here it is, here it is  $I_0 e^{\frac{AV_d}{kT}} - 1$  minus  $I_{sh}$  is  $V_d$  by ... is equal to ...

We need another bit of expansion, because  $V_d$  is the point here, diode voltage, with this point assumed to be ground and so, the diode voltage has to be expressed in terms of the load voltage, which is  $I_{ph}$  minus  $I_{naught e}$  to the power  $A$ . Now here  $V_L$  plus  $I_L R_s$  minus  $1$  minus, here also  $V_L$ , where  $V_L$  is this one, load voltage and here is a load current plus  $I_L R_s$  by  $R_{sh}$  is equal to  $I_a$ . So, this was the essential equation.

(Refer Slide Time: 3:59)



Now, from here we have also seen that the V-I characteristic where this is the V axis, this is the I axis, takes this form; so far so good. Now, with this, on the basis of this, we are trying to understand what happens to a photovoltaic panel when say it ages, when the age increases. See, for a mechanical device, it is not difficult to understand what happens as age increases, because things wear out. There are moving parts, they rub against each other, so there will be lots of natural things to happen when they age, while it is often difficult for people to understand what happens to a photovoltaic panel when it ages, because it is static device.

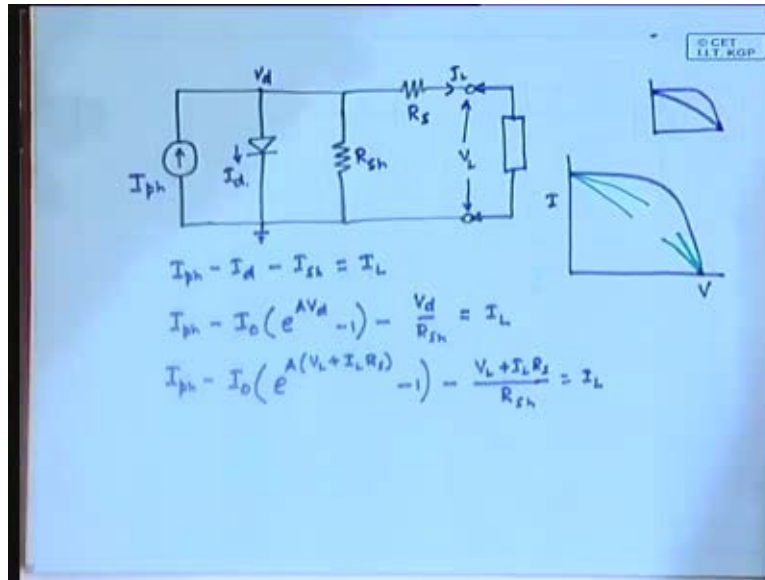
Now what happens is firstly, with weathering or weather action the conductivity of the silicon, the quality of the silicon, because things, impurities tend to get in, because of that the conductivity changes and where will be the effect of that?  $R_s$ ;  $R_s$ , because that is

the, that is the way the electrons are passing and they now encounter a larger resistance. The other effect is that as you have understood the p n junction is somewhat extended and on top of it, you have the fingers, the metal fingers to collect the charge, right. The metal fingers are collecting the charge and below that it is the silicon and here is the metal. Now, with age what happens is that the metal sort of diffuses into the electron, into the semiconductor material. As a result, the n layer that is very thin, n layer is very thin and if the metal in some places get in, what does it do? It sort of shorts the pn junction. What will be the effect as seen in the equivalent circuit?

It will be reduction in  $R_{sh}$ . Why because, that increases the recombination. The amount of charges that was separated before they actually can go through, pass through the load, they recombine because of the shorting. So, with age the series resistance goes up. The shunt resistance goes down and as a result the efficiency of the .... cell goes down. Now exactly what are the effects of these two? Let us try to figure it out. Here is the equation that ultimately leads to this curve. If I ask you where is the effect of  $R_s$  manifested, can you tell from the equation, from common sense? As you go on this curve, what is happening? Here is the high value of the voltage and low value of the current and here is the low value of the voltage and high value of the current.

So,  $R_{sh}$  is connected in a place where you have  $I_L$  directly passing through it. So, if  $I_L$  is very small, there  $R_s$  will have very little effect. So,  $R_s$  will have maximum effect where the  $I_L$  is large, around this part of the curve, right. So, in actuality, the effect of  $R_s$ , the series resistance is manifested in the slope of the curve at this point.

(Refer Slide Time: 7:52)



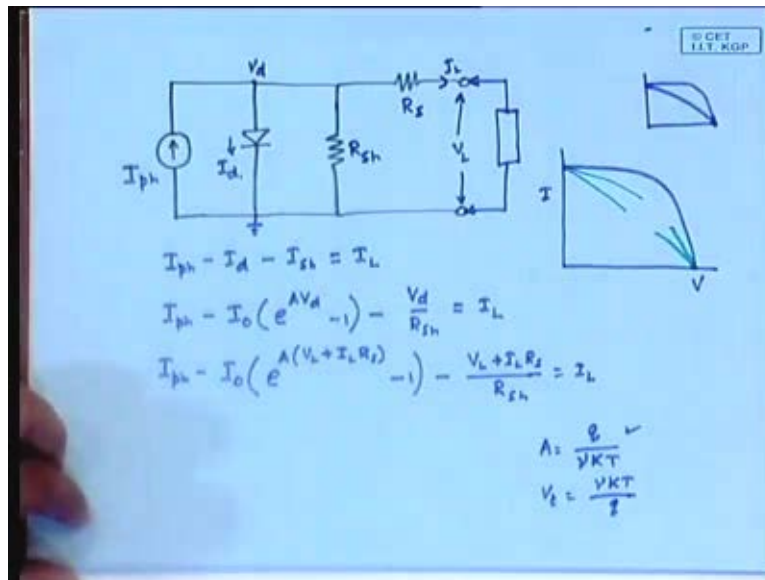
So, it will become like this, with increase in  $R_s$ . Likewise, see, if the load current is large and the load voltage is small, then what is the effect of  $R_{sh}$ ?  $R_{sh}$  will have any effect if this voltage is large and if this voltage is very small like here,  $R_{sh}$  will have very small effect, right. So, the effect of  $R_{sh}$  is manifested in this slope. So, as you have these,  $R_s$  going up and  $R_{sh}$  going down, you have the curve that was actually like this, actually like this with a good fill factor slowly becoming like this. Notice the  $V_{oc}$  and  $I_{sc}$  remain the same, well almost. Yet, the power that you can get out of it goes down, because the fill factor goes down.

So, if you now specify it, you will say that it still produces the same open circuit voltage and often people do not understand this. If you measure it, the voltage is still the same. Yet, the cell is not now as productive and this is also true for badly manufactured panels. When you buy a panel from the market, you never know. If you, if you simply measure with a voltmeter what is the voltage being produced, you find its fine and things are like this here, but yet the panel can be bad. So, it is often necessary to actually measure this characteristic in order to understand whether I am buying the right panel or not. Badly manufactured panels will have a characteristic like this not like that.

So, the effect of these two would be like this and as a panel ages, depending on which side is actually deteriorating faster, you can easily understand what kind of effect it is having. So, it is also possible to figure out which part is actually deteriorating faster. But, often it is not possible to take corrective action, because this is a solid thing, you cannot really change it. So, you only have to understand when you really need to replace it, but normally a photovoltaic panel runs fine for 20 years. So, this part is understood I guess.

How to solve some kind of problems? The problems can be, for example if we give all the parameters in the photovoltaic cell and ask you what should be the correct resistance to connect to it, you will be able to say and how do you work it out? Suppose I give you  $I_{ph}$  or I give you the incident solar radiation and what is the factor by which the incident solar radiation is converted to  $I_{ph}$ , either of the two, we also give the parameters of the diode meaning that I give you  $I_0$  and this  $A$  factor. By the way, in some books you will find that, what was the content of this  $A$  factor?

(Refer Slide Time: 11:42)

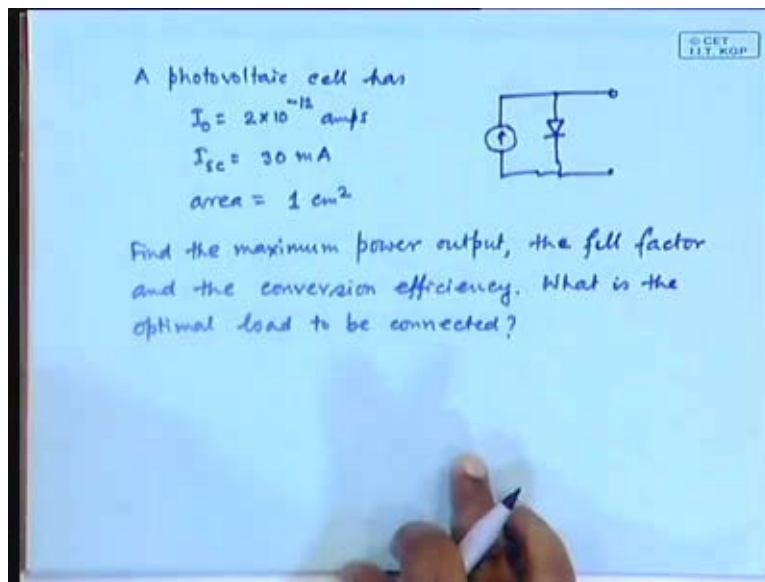


$A$  was  $q$  by, yes, there was these factors. Out of this,  $q$  is a constant thing,  $K$  is a constant thing,  $T$  is the temperature. This is a curve fitting constant. In some books you will find that this factor is ignored, do not be confused by it. In some books you will find this is

given as  $q$  by  $KT$ , so do not be confused. Normally you do have to assume a curve fitting constant whose value need not actually be 1, has to be found out from actual measurement of the diode characteristics. In some books you will find that its reciprocal is called  $V_t$  which is because this will have the unit of a voltage, so they call it  $V_t$ , but nevertheless for our purpose we are calling it like this.

Now if you are given a problem, for example say, I give you a problem like this.

(Refer Slide Time: 12:58)



A photovoltaic cell has  
 $I_0 = 2 \times 10^{-12}$  amps  
 $I_{sc} = 30$  mA  
area =  $1 \text{ cm}^2$

Find the maximum power output, the fill factor and the conversion efficiency. What is the optimal load to be connected?

The diagram shows a circuit model of a photovoltaic cell. It consists of a current source (represented by a circle with an arrow) in parallel with a diode (represented by a triangle with a vertical line) and a load resistor (represented by a rectangle). The current source and diode are connected in parallel, and this combination is connected in series with the load resistor.

Find the maximum power output, the fill factor and now, in this case I have not given the  $R_L$  and  $R_{sh}$ . If that is so, you will assume  $R_L$  to be zero and  $R_{sh}$  to be infinity. So, the photovoltaic cell is just represented as your current source, the diode, connect to the load, simple. Then, you can do the hand, do the calculation by hand actually. If you have this, then you need a little bit more complicated calculation, but it is essentially the same. So, how will you proceed? How will you proceed?

(Refer Slide Time: 15:21)

$I_{ph} - I_d - I_{sh} = I_L$   
 $I_{ph} - I_0 (e^{AV_d} - 1) - \frac{V_d}{R_{sh}} = I_L$   
 $I_{ph} - I_0 (e^{A(V_L + I_L R_s)} - 1) - \frac{V_L + I_L R_s}{R_{sh}} = I_L$

$A = \frac{q}{kT}$   
 $V_t = \frac{kT}{q}$

First, you know that from here you can find out  $V_{oc}$ ; you have already seen that, open circuit voltage. So, how do you find the open circuit voltage? Simply by assuming  $I_L$  to be zero; put  $I_L$  equal to zero in this equation. If  $I_L$  is equal to zero,  $R_s$  has no value. So,  $R_s$  automatically goes off. You can also, as I said, ignore  $R_{sh}$  assuming that it is infinite. So, you have an expression for open circuit voltage, you can find open circuit voltage. The short circuit current is given.

(Refer Slide Time: 16:00)

A photovoltaic cell has

$I_0 = 2 \times 10^{-12}$  amps  
 $I_{sc} = 30$  mA  
 area =  $1 \text{ cm}^2$

Find the maximum power output, the fill factor and the conversion efficiency. What is the optimal load to be connected?

V	0.5	0.52	0.53	0.54	0.56
I	29.6	29.0	28.6	27.9	25.5
P	14.8	15.1	15.2	15.1	14.2

So, you have, you have this, you have that and naturally you have this, fine. What you, in addition you need to find out maximum power point. I need to find this in order to find the fill factor. So, you have this, you have that and you need to find this. How do you find the maximum power point from the data available? All you need to do is for different values of the voltage, calculate the current. Can you do that? Not difficult at all, because all you need to do is to put those assumptions into this equation, make it simple enough and simply put the values, thereby you get the current as a function of the voltage. Suppose for example, for these once you will get value something like this; so, for different voltages I am writing the current. You will get for 0.5 volt it is 29.6 milliamperes, 0.52 you will get 29.0, then 0.53, you will get 28.6, 0.54 you will get 27.9. I am just shortening by not asking you to actually press. If you press the calculator, if you do it you will get these values; 0.56 you will get 25.5. So, simply by putting these values into that equation you have calculated this.

What is the power? Power is the product of this. So, product, you will again be able to simply write down. The product should be, here it is 14.8, here it is 15.1, here it is 15.2, here it is again 15.1, here it is 14.3. So, you can see it is going up, up and finally it is going down and here is the value at which, at least to the resolution at which you have calculated this gives the maximum power. Normally one would be required. If you have found the gross position, you would be required to calculate the intermediate positions, so that you get more accurate, but nevertheless at that level of resolution, this is fine. So, you know that you need this value of the voltage and this value of the current. So, here is a voltage here is a current, now you can calculate the fill factor. Fill factor is nothing but this area divided by this area.

What is the optimal value of resistance you need to connect? Resistance is nothing but voltage by current. So, here is the voltage, here is the current.

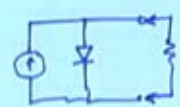



(Refer Slide Time: 19:35)

A photovoltaic cell has

$I_0 = 2 \times 10^{-12}$  amps  
 $I_{sc} = 30$  mA  
 area =  $1 \text{ cm}^2$

Find the maximum power output, the fill factor and the conversion efficiency. What is the optimal load to be connected?

V	0.5	0.52	0.53	0.54	0.56
I	29.6	29.0	28.6	27.9	25.5
P	14.8	15.1	<u>15.2</u>	15.1	14.3

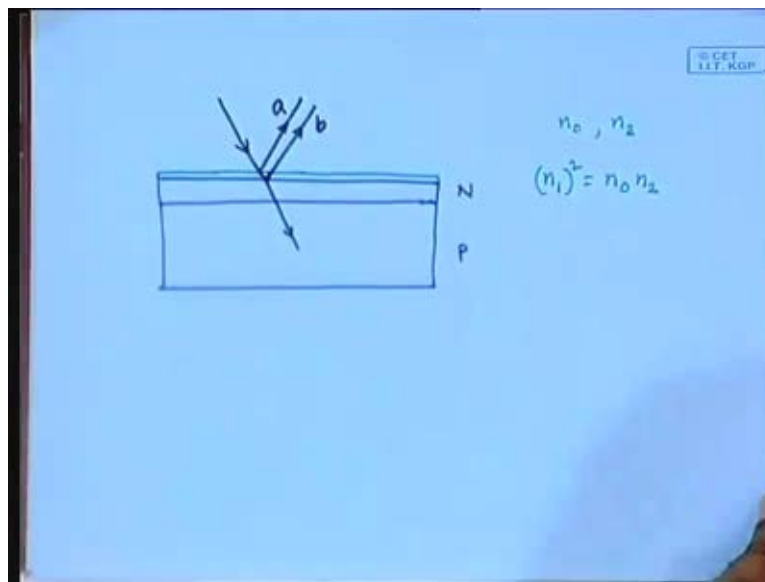
That is what you are talking about and here is the resistance you have connected. So, the resistance is nothing but the voltage by current. You know the voltage, you know the current; divide that you get the resistance. Optimally, that is the resistance you have to connect in order to get the maximum power, clear. That is how problems are to be solved in, when you are actually given problems in the exams that is how you do it. Normally when we give, in the exams we will try to make it simple enough, so that it can be done with a calculator, but when we give assignments, then you have to do with a computer. Then, you will have to consider  $R_s$ ,  $R_{sh}$  and all that, clear.

Now, let us come to the question of what produces the inefficiency? One source of inefficiency, I have already said, is that out of the whole solar spectrum that is coming, not the whole can be used. Why? Because, silicon has a specific band gap and band gap energy is like 1.1 volts. So, anything below that 1.1 volts will not be able to create a charge separation. So, electron hole pair will not be created, still it will be absorbed. What happens to that energy? It goes as heat. The incident solar radiation spectrum also has those frequencies, whose energy is bigger than 1.1 electron volt; larger than that. So, what happens to that excess one? That also goes as heat. So, we actually utilize that

amount of energy which is essentially very close to that band gap energy. The rest of it goes as heat. That is one source of inefficiency.

Another major source of inefficiency is simple reflection, because the top surface is a flat and quite plain surface, there will be deflection and in fact 40% is lost by reflection; 40% is quite a large amount. Fortunately we have ways of arresting much of it. How is it done? The idea is quite simple.

(Refer Slide Time: 22:17)



Supposing you have a, you have say, a semiconductor layer. You have the N over P. So, suppose here is the, so this is the N part, this is the P part and here is a junction. Now, on top of it, if you apply a thin layer of some transparent material whose refractive index is such, the refractive index of that material has to be carefully chosen, also the thickness has to be carefully chosen, normally the air refractive index is say,  $n_0$  and this material silicon's refractive index say  $n_2$ , then this material should have refractive index  $n_1$  square is equal to  $n_0 n_2$  and there are materials that have this kind of refractive index.

Now, if you choose that material and lay a small thin layer of thickness about one third the wave length of one of the frequencies, one of, one of the colours in the incident light, so what will happen for that colour? What will happen is that a part, the wave will, it will come in and then it will, a part will go in, another part will go in all right, but there will be another part that will be reflected out. Some part will be reflected off here and some part will be reflected off here and it is possible to make this coating such that these two, say I call it a and b have 180 degree out of phase.

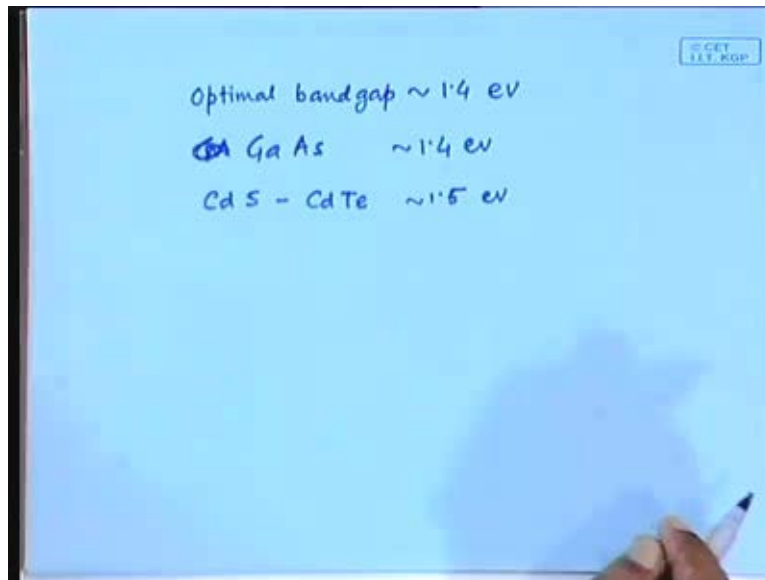
When that happens, what will happen? These two guys will cancel each other. If that is so, the reflection will go down significantly. In fact, if you do not lay any antireflective coating like this, then as I told you, the reflection is of the order 40%, while if you put this kind of a specifically chosen antireflective coating, it can be brought down to something like 6 to 8%, a large loss, large saving. The rest of it actually goes in. So, this is one way of cutting down the loss due to reflection. So, what is actually done? Some kind of a material is put as the top and that depends on this base material, obviously because of this factor. Air is common all right, but  $n^2$  is the refractive index of the silicon, of that particular amount of doping. So, that is very specific and depending on that you will have to choose some material which will act as the antireflective coating and it does because of this.

Now, as I told you, the thickness has to be tuned to the specific wavelength, because it has to be about one third of the wavelength. Now, do you choose it for red or blue or green, what? Violet, not really because some part in the red region is actually non-productive, because it has energy that is less than the band gap energy. Out of the ones that are productive, there will be some frequency which is maximally productive, which is maximally productive. Normally, this is tuned to that frequency like blue, but not in the violet. So, this is how the antireflective coatings are used in order to increase the ... and this is another that goes down, that degrades. If you look at old photovoltaic cells, you will see the colouring is different than the new ones. The new ones have different type of texture, colouring that is mainly contributed not by the silicon, but by the antireflective

coating and that is another thing that goes down, degrades over the years as time progresses. So, you have understood the idea of the antireflective coating.

Now, let us come to the issue of band gap. What do you choose as the band gap? As you understand, various materials will have different band gaps. Silicon has 1.1 all right, but you could as well choose something else. Now, where should we optimally locate the band gap? If you locate the band gap too high, then most of the incident solar radiation will not produce anything, because they will not be able to knock the electron from the location. So, you cannot choose it too high. Then, what is the problem in choosing it too low, say 0.3, 0.4? No, you cannot do that, because the open circuit voltage is dependent on that. The open circuit voltage is dependent on that and if you choose it low, the open circuit voltage goes down and as a result the total power also goes down. So, there has to be some kind of a balance, some kind of a trade off and it is now more or less agreed by people in the trade that the optimal band gap is something like 1.4 electron volts.

(Refer Slide Time: 28:22)



So, optimal band gap, obviously silicon does not have that band gap. Its band gap is lower than that. So, what are the other materials being considered? One prime material that has the band gap exactly 1.4 is gallium arsenide, sorry, I, gallium arsenide has band

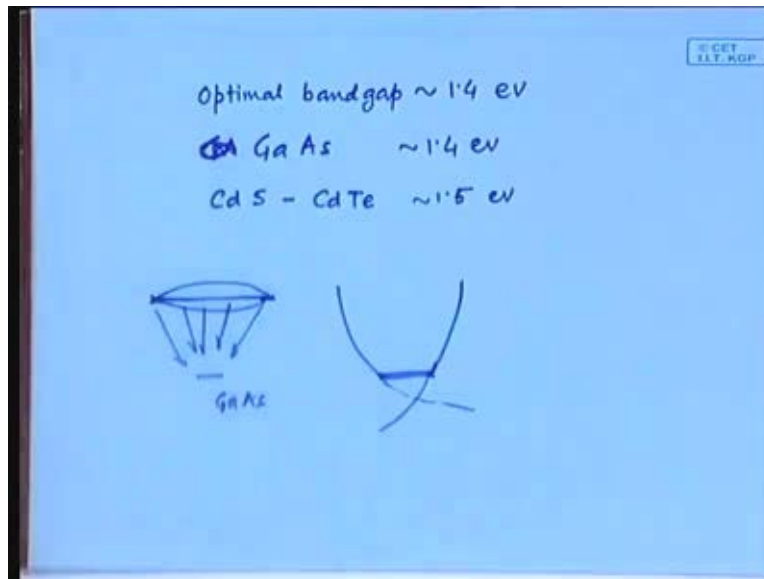
gap approximately 1.4. So, this is one good choice for a material. Yes, it is a good choice for a material and gallium arsenide solar cells are in operation and they are manufactured, they are available in the market. Though none is being manufactured within India, but they are available. There are other materials that are being considered, for example cadmium sulphide, cadmium telluride.

Now, where you have the n-type and the p-type constructed by the same material, it is called a homo junction and if these are constructed by two different materials it is called hetero junction. As you can see, this is a hetero junction kind of construction. So, the main p-type material is cadmium telluride, while the n-type material is cadmium sulphide. It also has a band gap something like .... I am talking about the cadmium telluride's band gap, because this would have a slightly different band gap. Similarly, there are other materials, which I will come to slowly. So, these are considered as candidates for construction of solar cells.

So, let us, let me now enumerate the directions in which research is progressing, so that later when you become full grown engineers, you might actually encounter this kind of materials and solar cells made of this kind of materials and so, you need to have some kind of initial exposure to that. Let us see how these are actually done. First, let us come to the gallium arsenide cell, solar cell. What is the characteristic of gallium arsenide? As I said, the band gap is very optimal, 1.4. It has another very desirable property that its performance does not degrade with the increase in the incident solar radiation, because in other materials like silicon, if you have a larger concentration that means larger amount of incident solar radiation is falling, then the temperature goes up and the character of the solar cell degrades with the temperature, because the temperature appears in the equation.

Now, in case of the gallium arsenide one specialty is that temperature does not degrade the characteristic and so, mostly gallium arsenide, because it is more expensive than silicon, never we think of making very large areas of gallium arsenide, but people do consider concentrating solar cells made of gallium arsenide. What is the, what is the character then?

(Refer Slide Time: 32:22)



The character would be, the whole scheme would be, where you have some kind of, some kind of concentrator. What kind of concentrator, I will come to that and here you have a smaller area of gallium arsenide solar cell, so that the light from the whole range is concentrating onto that and this has an incident solar radiation about 5 to 6 times the actual incident solar radiation over a standard area. What kind of concentrator can it be? Have I, have you already learnt concentrators? Yes, yes, right. So, you have learnt that there are a few types of concentrators. One is where it is reflecting concentrator, the other is refracting concentrator and out of the refracting concentrators, you have learnt that a whole big lens is of no use. We normally use Fresnel lenses. Yes, the Fresnel lenses are also considered in conjunction with gallium arsenide solar cells. So, very rarely you will find the gallium arsenide solar cells are considered as just stand alone system, they are used in conjunction with some kind of a concentrator.

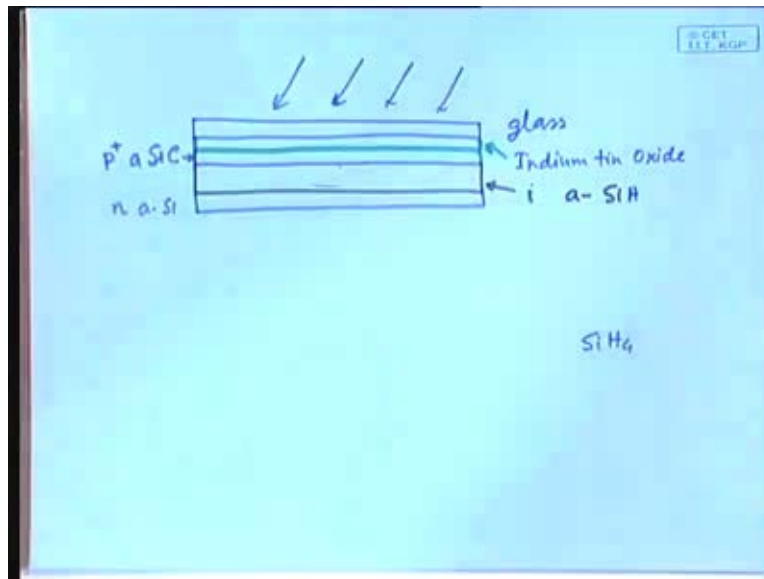
The other type of concentrator that is considered is the reflecting concentrator and you have learnt what kind of reflecting concentrators? For example the Winston's profile, where you have and here is the gallium arsenide solar cell. These are two parabolas and here this parabola has this as the focus and this parabola has this as the focus. That is the construction. So, you can have some kind of an alumina reflecting bowl and on the, on

the bottom of it you have a gallium arsenide solar cell. Now, this gallium arsenide solar cell is actually manufactured in the similar kind of structure as this thing, the single crystal silicon solar cell, because this also is made as a single crystal of gallium arsenide. So, you have got the single crystal gallium arsenide on which in the same way you have a deposition of n layer of gallium arsenide and you have the pn junction. The whole problem is that this is far more expensive than silicon. That is why all these considerations are generally used, clear, fine.

Next, let us come to the next level of development. As I told you that silicon has three types of, we can make solar cell out of three types of silicon. One is single crystal, two is polycrystalline and three is amorphous silicon. What is the advantage of amorphous silicon? It can be made in terms of thin films. So, the bulk of silicon that is necessary is far less, far less about 100 times less and as result of which these are very cheap, but the efficiency is less. People have considered different constructions of, different materials to make thin film solar cells. Because the amount that is necessary is very small, the cost can be reduced. But, let us first understand the structure of the amorphous silicon solar cell.

I, earlier I have talked about the single crystal solar cell, but I did not talk about the amorphous silicon solar cell. So, let me, let me talk about it. In the amorphous silicon solar cell you have first, something has to provide the support, right, something has to provide the mechanical strength and that is normally a glass layer.

(Refer Slide Time: 36:22)



So, we have first a glass layer. That is what provides the strength and instead of it growing above the glass layer, normally it is grown below the glass layer, so that the light comes like this and the solar cell is actually below, down there at this, this level. First, what should go below the glass layer? Imagine, the light is coming from that side through the glass into the silicon and what did I say should go first? An antireflective coating that should go first and its refractive index should be such which satisfies that equation between glass and the silicon and the material of choice in this case is indium tin oxide. This also has the property that that acts, here is the glass, here is, here I will show how the thing is, but after all the solar cell is here, so what has to be at the top, top surface? In a normal single crystal solar cell, what is there at the top surface? You have to collect the charge, you have to collect the charge and the collection of the charge is done by means of the fingers, the metal fingers.

In this case, can you do that? No, you cannot do that. So, what is done? A trick is that the indium tin oxide also has the property that it is conducting. As a result, that also acts as the charge collector; that can also act as a charge collector. So, here you have a layer of indium tin oxide ....., as the top charge collecting layer. Below that you have a layer of, it is amorphous silicon carbide layer which acts as the, acts as the P layer, not the N layer.



So, it is P or may be P plus I can write. So, here is the silicon carbide layer. Below that you have the proper amorphous silicon layer which is also very thin, remember. The thinness is of the order of 1 micron, 1 micrometer. So, below that you have a layer. Now, this layer is called i layer or the intermediate or intrinsic amorphous silicon layer, amorphous Si.

Now, here is a, here is a, here is a point that you have to understand. How is it done? It is actually, all these layers are actually deposited one after the other. That means when it is manufactured, the glass is laid like this and things are deposited. First you have got the indium tin oxide layer deposited and stuff like that. Now, when this layer is deposited, it is actually deposited out of silane gas. Silane is  $\text{Si H}_4$ ,  $\text{Si H}_4$ . So, first this gas is introduced in that chamber and then it is broken up through electrical discharges. So, you have to, when it breaks up you have got the silicon separated out which deposits onto this glass.

While it does so, silicon will have a lot of dangling bonds then. Some of these dangling bonds are satisfied by that excess hydrogen which is again separated out that is also in that environment. That hydrogen sort of satisfies some of the dangling bonds, as a result forms what is known as not exactly silicon, but silicon hydrogen alloy kind of thing. It contains about 10 to 20% hydrogen and as a result, some of the dangling bonds are satisfied and dangling bonds as I told you are the recombination centers that reduce the recombination. So, that is what is desired. So, in this part you have Si H and below that you have again a layer. This is n layer of amorphous silicon. So, you see, here is a p layer, here is the n layer and here is the thin amorphous silicon layer, silicon hydrogen layer.

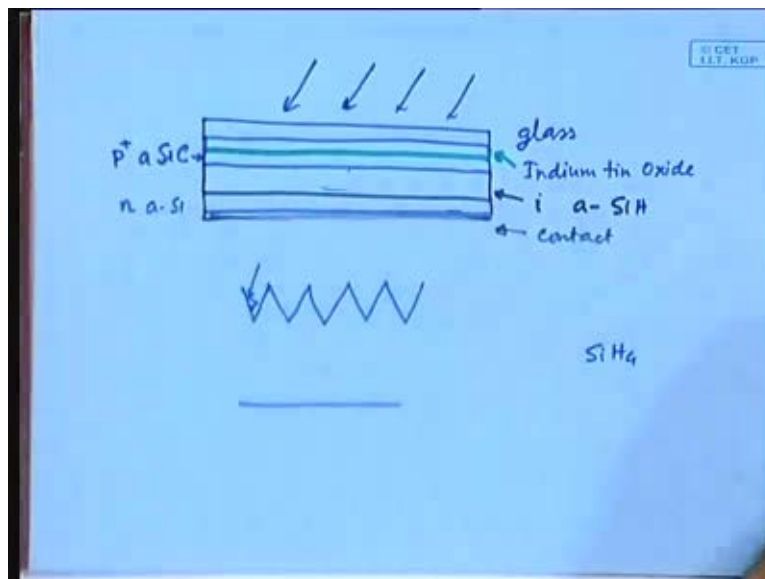
What happens is that in this layer you have got electrical potential. So, actually the light goes into this layer and because it experiences electrical potential that is why the charge separation takes place which goes to here and here. Is that clear? So, it is necessary that this layer should be very thin. In fact all these layers are very thin. So, these are all of micron level. So, the whole thing is a very, very thin, but layers after layers structure and

that is what you see in your calculator solar cells, you know. In the calculator, you see the solar cells, small solar cells; these are all amorphous silicon solar cells. Nowadays, even people have put these amorphous silicon solar cells into sheets that can be rolled.

So, instead of glass, you put some plastic material on which the whole thing is grown and then things can be rolled and you can put it on top of anything, even on top of aeroplanes. So, there have been experimental planes that, whose wings are covered with such photovoltaic cells and ultimately that does the problem, no fueling is necessary, the high altitude planes. These are of course experimental planes. No, not only experimental planes, but also military ..... planes also are done like that. So, this is the structure of the amorphous silicon solar cell. Is that clear?

In case of, in order to, okay one thing you have to understand. This is after all silicon and silicon's absorptivity is very small. So, if it is very thin, what will happen? The light will actually go through without being absorbed. So, how to, how to overcome that problem?

(Refer Slide Time: 44:17)

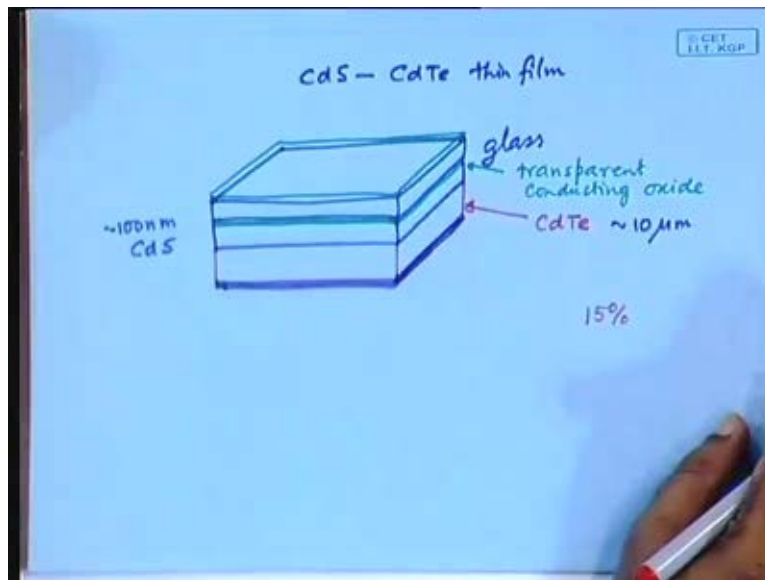


The way people overcome that problem is firstly to make the top layer not as a flat layer, but something like this. As a result, the light that is coming in has to go through multiple

reflections and ultimately will go in. That is one trick that is normally used. The second trick that is used is here at the bottom here, you have to have one conducting layer, right. I forgot to put that. Here there has to be a conducting layer, because you have to collect the charge. So, here is a contact layer. That contact layer is made reflecting, so that whatever goes up to this point is again reflected back. So, actually the light goes through multiple reflections between these two, ultimately has to be absorbed. So, this is the other trick by which people try to improve the efficiency of this kind of solar cells.

Let us now come to the construction of the other types of solar cells, the cadmium sulphide, cadmium telluride that is a very strong contender nowadays. In this case the structure is something like this. I will show again from the top.

(Refer Slide Time: 45:49)



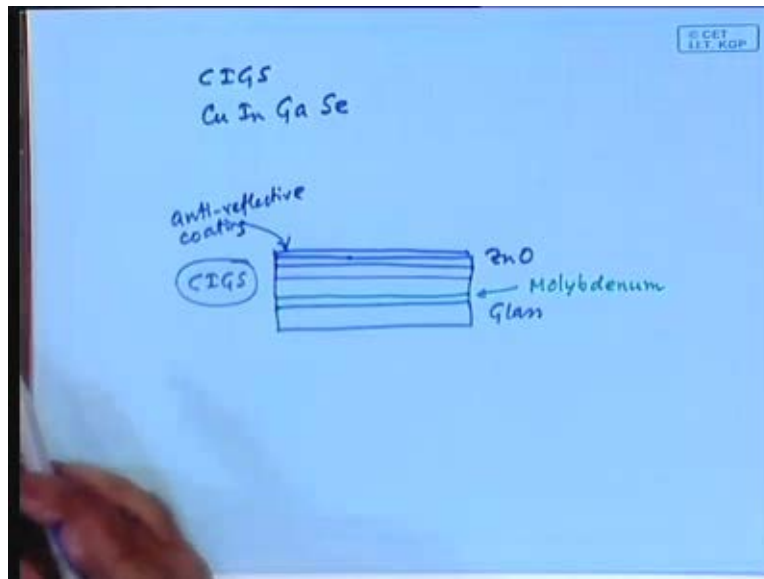
First you have the glass cover. Let us start from there. On top of the glass, so that the glass does not reflect, one has to put antireflective coating here. So, this side you have got one antireflective coating there whose refractive index is tuned to be between the air and the glass, good. So, very little goes off, goes through the glass. Below that you have, what should there be at this point just below the glass? What is the first one? Has to be top metal contact, right; so, this is a transparent, some conducting oxide. As I told you, this

could be indium tin oxide, sometimes simply tin oxide. So, first this one. Now, then you have cadmium sulphide layer. First you have the cadmium sulphide layer it is about 100 nanometers, very thin, cadmium sulphide layer.

Now below the cadmium sulphide layer, you have the main material, cadmium telluride. So, the cadmium telluride is your p layer, CdS is your n layer, you have got a hetero junction and this is what does the job and below that you have normally a, what has to be under that? Another metal contact and this metal contact is often a gold contact, very thin layer of gold, gold or silver. So, this is the total structure of this kind of solar cell. This is CdS - CdTe, thin film. Now, cadmium telluride has approximately 10 micrometer size. So, you see, the whole thing put together is a very thin layer again. So, this is again a thin film solar cell and this has very good efficiency.

So, these kinds of materials are actually considered nowadays for thin film solar cells. Its efficiency has gone up to something like 12 to 15%. So, approximately 15% efficiency has been achieved with copper sulphide, cadmium sulphide solar cells, while in case of amorphous silicon solar cell thin film, we have not been able to achieve efficiency more than 10%. So, is there any question about it? This one, this is actually one of the main contenders and you will find that in commercial market within say from 5-6 years.

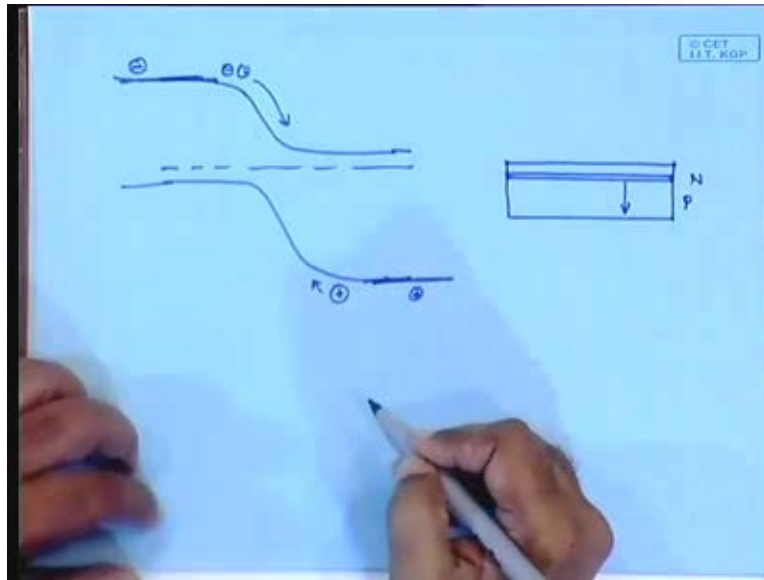
(Refer Slide Time: 50:26)



Another type of material that is being considered nowadays is called CIGS, where CIGS stands for Copper indium gallium selenium. All these put together makes a material that has again a band gap very close to what you want and that is again a contender for a thin film solar cell nowadays and here also your structure is quite similar, but here in this case the glass is at the bottom. So, bottom layer is glass. On top of it we have the bottom contact. The bottom contact is provided by a layer of molybdenum. Then, on top of it you will have the CIGS layer.

The deposition process of the CIGS is rather complicated because, one, it is difficult to discuss because these are all again changing all the time. There is a indium gallium mixture which is put in first and then that is reacted with copper and selenium and that kind of very complicated process of deposition of this goes on and depending on the deposition you have, it is also possible to produce band, continuous band bending. I will, I will come to that later. First, understand that this is CIGS and then on top of that you have a ZnO layer as the top collecting surface. This CIGS layer has the pn, it is a homo junction and then on top of that you have got the antireflective. So, that is the structure, but in this case the deposition process of the CIGS is rather complicated. But, one concept which I forgot to mention, that I have to bring in now.

(Refer Slide Time: 53:23)



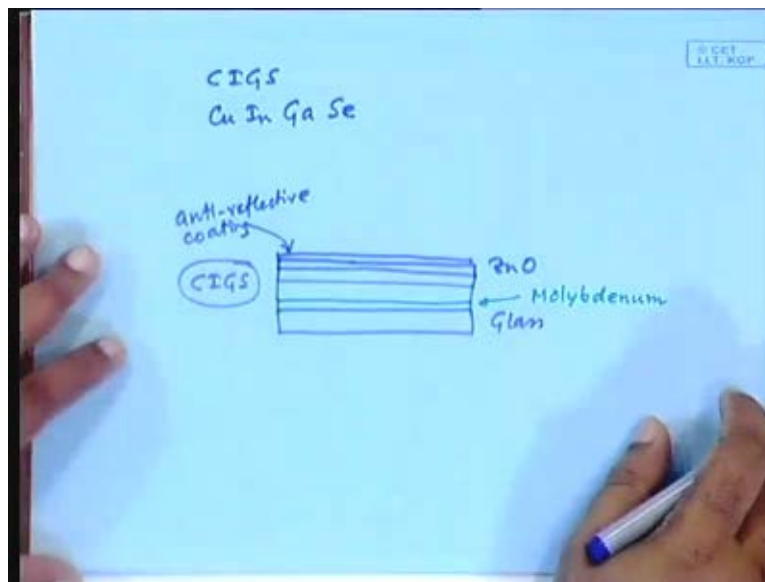
You have seen that the elementary process by which the charge separation takes place is the pn junction, in which what happens is equalization of the Fermi level and you have got this one going like this and this one going like this and if you have the electrons produced, they flow down and the holes produced, they flow up. That is an essential thing that you have learnt. Now, here it is flat and here also it is flat. If it is flat here and some electron is produced here, what will you see? It will not be able to see the, at some distance there is a band bending. So, it will actually move in any random direction, it will not flow down the hill. If a hole is produced here, same problem. So, normally one way to avoid this is to produce a graded doping instead of, what you have learnt is that you will have a P layer and a thin N layer and on top of that the metal contact. So, here is the P, here is N.

Now, this P, N is anyway very thin. So, N side is anyway very thin, so it does not really matter. The electric field goes through the whole length no problem, but here the P layer is large. If the P layer is thick, you cannot have the whole electric field going into the whole P region. So, in this case you have a graded doped structure which means the doping here is larger, doping here is relatively smaller and then, here is N. If it is like this,

then the electric field actually has a slope. It will have a slope like this and things will flow in. Is that clear? So, this is the, this is called the graded doped structure.

Now, this is very common nowadays, but if you produce the whole P layer as just one and then grow on top it the N layer, obviously you cannot do that. So, there has to be some additional doping that has to be put at the bottom level of it. So, there are technologies for doing that in silicon as well as in these materials.

(Refer Slide Time: 55:49)



For example, when I was talking about the CIGS deposition, the CIGS and their individual components concentration is varied as it is deposited and as a result of which you will have, you automatically produce a graded band gap. So, you have this technology in built in all the different types of production technology that we have talked about, clear. More or less we have covered photovoltaic cells, photovoltaic panels; fine. That will be all for this particular topic. From the next class we will go to another.

Thank you!