Processing of Semiconducting Materials
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Lecture - 40
Materials for Photovoltaics

This is the last topic in this series of lectures from the processing of semiconducting materials. In earlier lectures, we have find that there are many materials, we have discussed particularly, the growth of the materials, the bulk crystal growth, the epitaxial kind of crystal growth. And then some processing like how the metallisation can be done, how the oxide layers, the dielectric layers can be deposited, what materials are used; different types of contacts, like the ohmic contacts, the schottky contact, all such processing technologies we have discussed. Today, we shall concentrate our attention on the materials, which are used for the photovoltaics, which popularly can be regarded as say solar cells or that kind of a device.

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Solar Cell

- Low maintenance, long lasting sources of energy
- Provides cost-effective power supplies for people remote from the main electricity grid
- Non-polluting and silent sources of electricity
- Convenient and flexible source of small amounts of power
- Renewable and sustainable power, as a means to reduce global warming
- In 2008, the global market for photovoltaic panels and equipment was valued at 5 billion dollars

So, you know that there are some appealing characteristics of the solar cell, it has low maintenance, long lasting sources of energy, it provides cost effective power supplies for people, removed from the main electricity grid, and it is non polluting and silent (( )) electricity, because it has no moving part. And it is convenient and flexible source of small amounts of power not always you have to feed to some grid, you can use as a standalone system on a roof top or inside your building or a room, and it is a renewable sustainable power, as a means to reduce global warming. And in 2008 the global market for photovoltaic panels and equipments was valued at 5 billion dollars, which is increasing day by day. So, in a nut shell we can say that the solar photovoltaics is very important device for or harnessing solar radiation into electricity.

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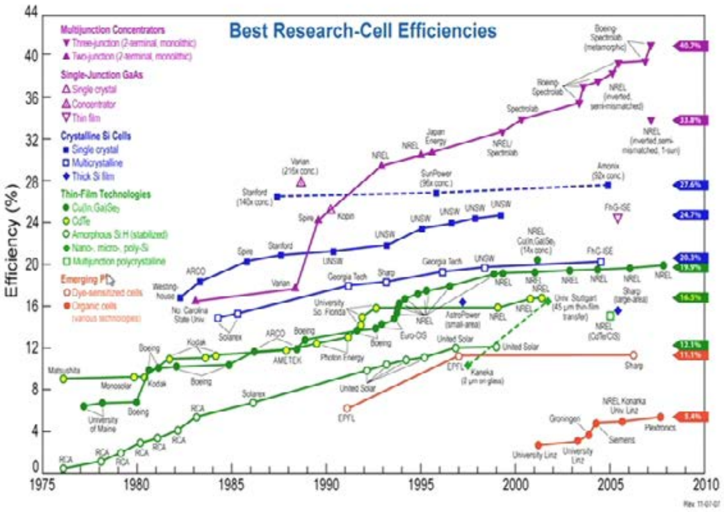

Then so far as the material parts are concerned, you can see that different materials are used, and in this view graph you can see that a large number of materials, which are shown in different colours, like say in this colour it is the multi junction concentrator cell, then single junction gallium arsenide, crystalline silicon then thin film technology, which can be used using the copper indium, gallium solenoid, cadmium telluride, amorphous silicon, micro, nano and polycrystalline materials, then multi junction polycrystalline cell. And also some of the emerging photovoltaic materials, which are say dye sensitized solar cells or organic solar cells, this is the emerging having low efficiency.

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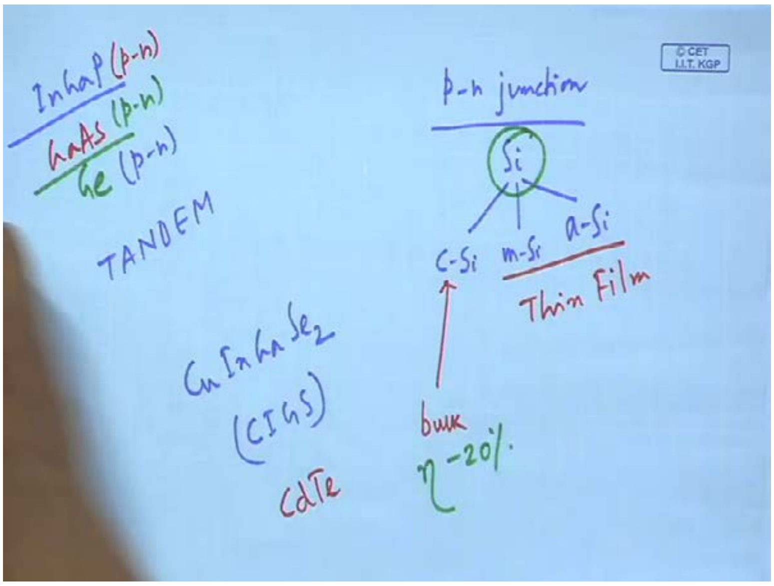

Now so far as these materials are concerned most of the solar cells, which are used as in the which are used in the domestic sector or which are available in commercial market are made of the silicon and p-n junction, and we know that silicon can be of 3 types, one is say crystalline silicon another is say multi crystalline silicon, and third one is say amorphous silicon. So, 3 types of silicon can be used for making the solar cells out of which the multi crystalline, and amorphous solar cells are basically the thin film devices, those are the thin film devices. And crystalline silicon it is the bulk solar cell, it is the bulk material and which is widely used and you know that in the present generation, it is almost 20 percentage efficiency is obtained using this crystalline silicon solar cell, which is often used in our domestic sector.

Now, apart from this silicon, you can see from this view graph that there are other types of cells say this one this colour, this maroon colour you see that now the efficiency is 40.7 percent, this is the 3 junction, three junction solar cell, multi junction solar cell, and you can see that it has started journey in 1982. And then there was a steep increase in the efficiency on y axis you can find the efficiency in percentage, and now it has attained greater than 40 percent efficiency. This cell is made up of 3 types of materials, because 3 junction are involved, and one is that this germanium, this germanium on which there is on germanium, there is gallium arsenide p-n junction is made, and at the top of it the gallium indium phosphate, indium gallium phosphate material is used.

So, you see that there are 3 types of junction, this is a p-n junction of indium gallium phosphate, this is a p-n junction of gallium arsenide, and another is the p-n junction of germanium, this kind of cell is known as the multi junction or tandem solar cell T A N D E M tandem solar cell, and this tandem solar cell has enormous efficiency, and which is often used in the space application in satellite communication, we can find that this kind of solar cells are used, which is made by the Boeing spectral lab or other kind of say in n r e l in Varian and so they are many inspire. So, many companies use this kind of technology for manufacturing the cell, and which has very high efficiency of 40 percent, another kind of cell you see that this dotted line, this dotted line is basically the single crystalline, and silicon solar cell, this is the this one single crystalline silicon solar cell, and this silicon solar cell has attained almost 25 percent efficiency.

These efficiencies; obviously in the large scale not on the commercial sector, and most of the silicon solar cell has been and designed or fabricated, and experimented in the university of south Wales in Australia. Now, other form of solar cells like the thin film technology, this greens are the thin film areas, and this is basically the 19.9 percent or around 20 percentage is the copper indium gallium solenoid solar cell, this is copper indium gallium, and the solenoid, actually disolenoid is used C I G S popularly known as C I G S , and this cell has achieved that 20 percent efficiency, and then this yellow dots with green circle, this is the cadmium telluride, this has almost 17 percent efficiency, 16.5 percent efficiency.

This is also a thin film solar cell, made of cadmium telluride C d T e. So, we see that apart from this different verities of silicon, like the crystalline silicon, multi crystalline silicon, amorphous silicon, other materials involve for the fabrication of solar cells are the copper indium gallium solenoid C I G S, C d T e cadmium telluride for tandem 3 junction, we can have compound semiconductor 3, 5 compound semiconductor solar cells made of germanium gallium arsenide and indium gallium phosphate. Other than this the emerging photovoltaic cell, say it is the dye sensitized cells and the organic cells, though we can find that the efficiency is very low for organic cell, it is almost 5.4 percent versus 6, 7 percent, the present day people have claimed that 8 percent efficiency, has been achieved.

And another one is the dye sensitized cells, which is make use of the dye for the solar radiation to absorb it has achieved 11 percent efficiency. So, in a nut shell we can see, that there are many types of materials, which are used, and apart from the silicon and those materials are regularly used for the fabrication of the solar cell.

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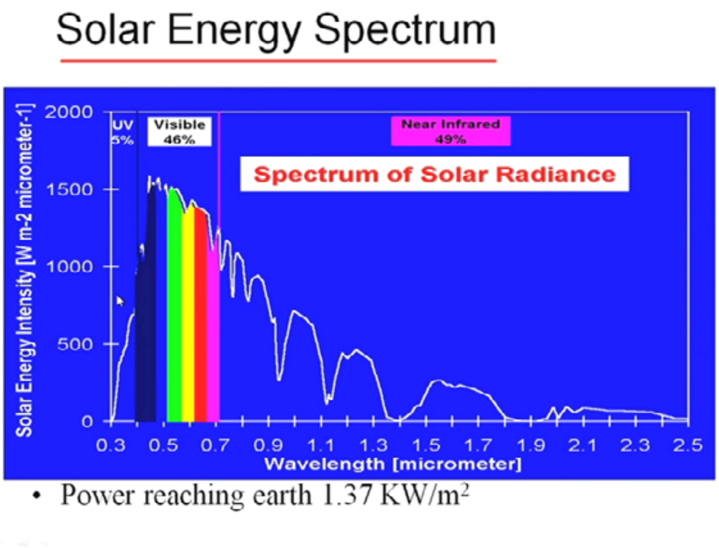

Solar Energy Spectrum

- Power reaching earth 1.37 KW/m²

Now, the problem is that why different materials we discuss. Here you see that the solar energy spectrum, which is available from the sun on the earth surface, you see that it contains 46 percent visible wavelength, 46 percent visible. So, this corresponds to basically the wave length say from 400 to 700 nanometer, then 49 percent is near infrared. So, this part is near infrared, which is above 700 nanometer to 2500 nanometre, and very small part of u v almost 5 percent reaches the earth atmosphere. So, the basic thing is that we have to choose materials in such a way, that it can absorb the most of the solar radiation, which is available on the earth surface.

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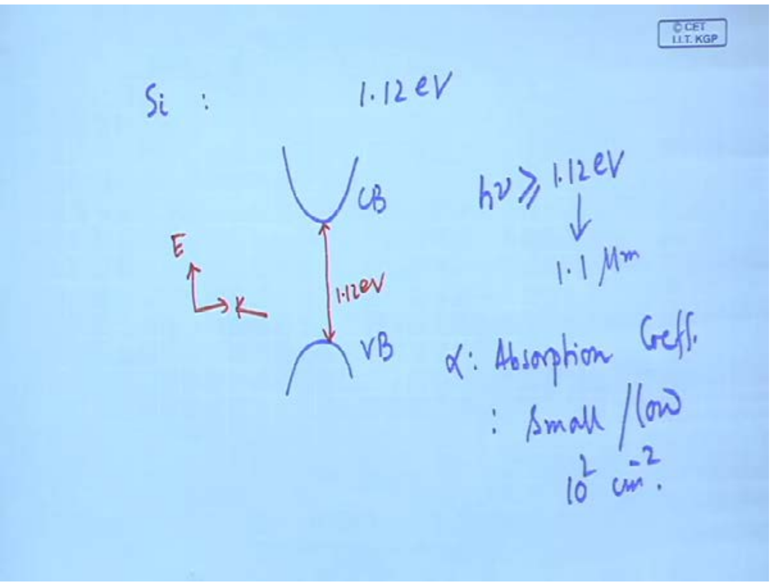

Now, if we take the example of say silicon, we know that silicon is an indirect band gap material having band gap 1.12 electron volt. Now when we talk about 1.12 electron volt, so it is the difference in energy between the conduction band bottom, and valence band top and this energy difference is 1.12 electron volt; this is the E K diagram. So, now this 1.12 means, that any solar radiation or any radiation h nu greater than equals to 1.12 electron volt energy, so any radiation having energy greater than or equals to 1.12 electron volt can be absorbed by the silicon. So, any energy which is less than 1.12 electron volt cannot be absorbed by silicon, so another problem is that with this 1.12 electron volt; that means, it corresponds to 1.1 micron.

So we see that 1.1 micron or less. So, theoretically most of the solar spectrum can be absorbed by the silicon, and unfortunately for silicon the absorption coefficient is very small, within this region of the wavelength, which it can absorb. So consequently though theoretically large portion of the solar energy spectrum can be absorbed by the silicon material, unfortunately because of its low absorption coefficient, the electron hole pair generation on absorption of the solar energy over silicon is very less. And another important aspect of silicon is that, one thing is that it has indirect band gap, band gap is 1.12 electron volt, and it has the absorption coefficient or alpha, which is known as the absorption coefficient.

Absorption coefficient it is small absorption coefficient is low it is almost 10 square per centimetre inverse. And if we compare with other type of material say gallium arsenide, copper indium gallium solenoid or cadmium telluride or in amorphous silicon, we shall find that it is greater than 10 square it is almost 10 to the power 4, 10 to the power 5 per centimetre square is the alpha value or the absorption coefficient value.

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Basic limitations of Si

- 1.12 eV; indirect type:
- Relatively lower carrier mobility (as compared to GaAs, etc.)
- Low absorption coefficient

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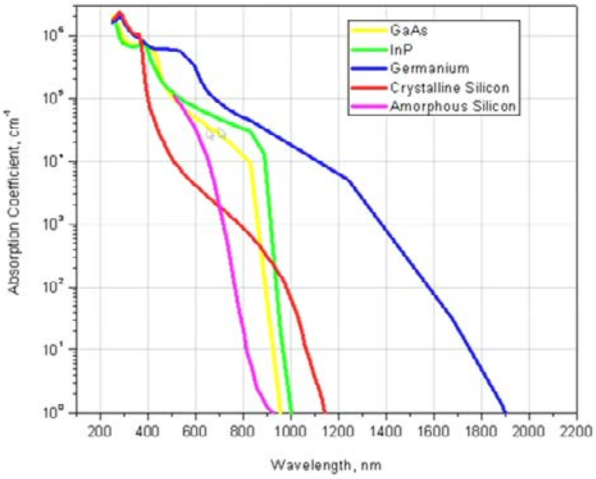

So, we can say that there are some limitation, basic limitation of the silicon is there, low absorption coefficient, you can see that this is the silicon and crystalline silicon, this red, and at around say its band gap, this absorption coefficient is very low, it is 10 square, only 10 square. And if we consider, with the if you if you compare this value with the amorphous silicon, which is the this pink one, you see that it is higher absorption coefficient than silicon at this wavelength or say if you consider the gallium arsenide or indium phosphate or germanium, they have higher absorption coefficient then silicon and another thing is that, it is relatively lower carrier mobility as compared to gallium arsenide and for very high efficiency.

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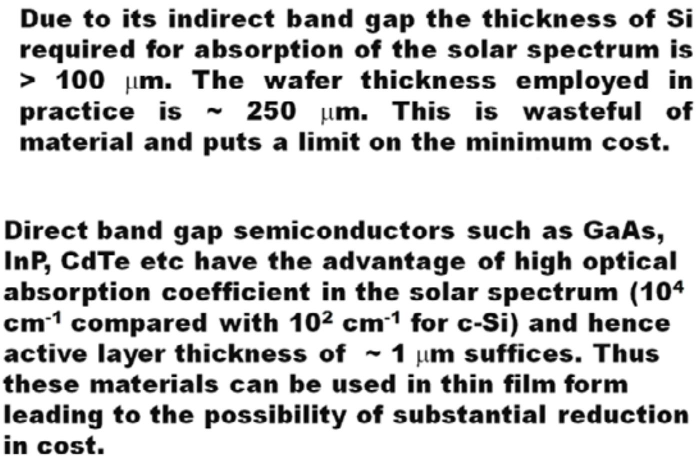

Due to its indirect band gap the thickness of Si required for absorption of the solar spectrum is > 100 μm. The wafer thickness employed in practice is ~ 250 μm. This is wasteful of material and puts a limit on the minimum cost.

Direct band gap semiconductors such as GaAs, InP, CdTe etc have the advantage of high optical absorption coefficient in the solar spectrum (10^4 cm^{-1} compared with 10^2 cm^{-1} for c-Si) and hence active layer thickness of ~ 1 μm suffices. Thus these materials can be used in thin film form leading to the possibility of substantial reduction in cost.

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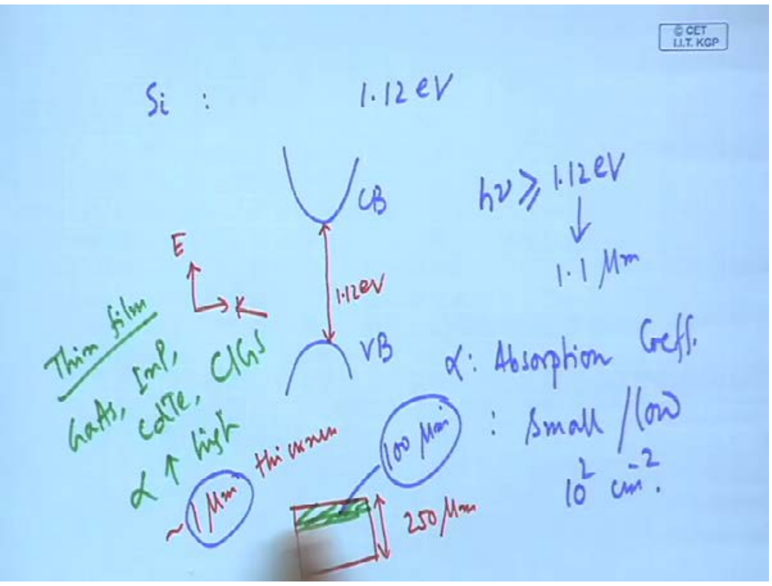

So, due to its indirect band gap, the thickness of silicon required for absorption of the solar spectrum is greater than 100 microns. So, the wafer thickness employed in practice is almost 250 micron. So, this is wasteful of material and puts a limit on the minimum cost; that means, suppose your crystalline silicon wafer is 250 micron or even in some cases it is 250 to 350, and only you are using 100 micron of it, you are using 100 micron of it.

So, then rest amount is wasteful. So, that is why you cannot reduce the cost of the silicon solar cell, because of this waste stage in the crystalline silicon material, which you know that can be obtained using the czochralski crystal growth or Bridgman crystal growth that, we have discussed earlier in this series of lectures, another thing is that direct band gap semiconductor. Such as gallium arsenide, indium phosphate, cadmium telluride etcetera have the advantage of high optical absorption coefficient in the solar spectrum, say 10 to the power 4 per centimetre compared to 10 square per centimetre.

So, hence the active layer thickness of 1micron is sufficient in case of the materials, which can be gallium arsenide indium phosphate or cadmium telluride, such this materials can be used in thin film form, leading to possibility of substantial reduction in cost. So that is very important thing that, if we use the thin film material, if we use the thin film material, then the material cost could be very less, and we know that for gallium arsenide, indium phosphate, cadmium telluride type of cell or C I G S, because its alpha is large, alpha is very large high alpha.

So, we can use small amount of the thickness to absorb the solar radiation, and it is almost 1 micron, can be used for making this type of a solar cell, where in case of crystalline silicon, we know that this is almost 100 microns. So, this is 100 micron, this is 1 micron for thin film, and the reason is that the alpha or the absorption coefficient is very high, in case of this material, which is 10 to the power 4 per centimetre compared with 10 square per centimetre for crystalline silicon.

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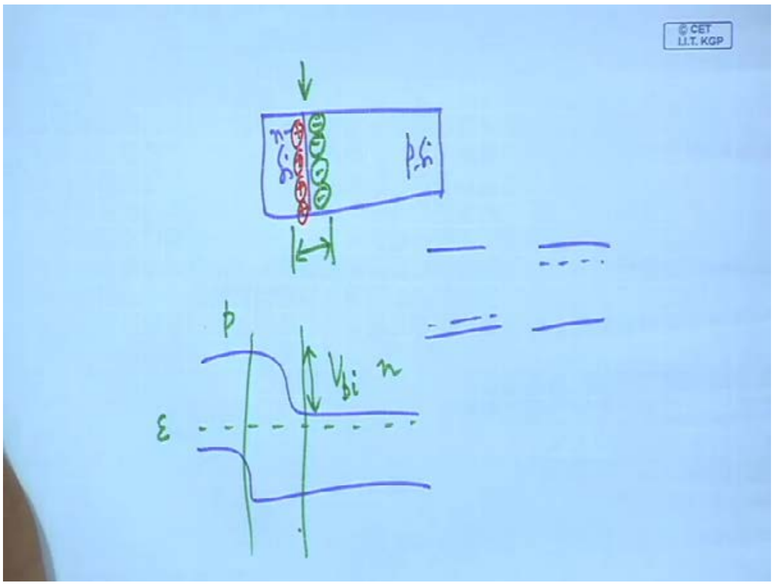

So, the basic idea is that we have to absorb the whole spectrum of light, because you know that when light falls on the material, if we discuss the physics of the p-n junction solar cell, we can see that and when a p-n junction is formed, say this is p type silicon, on which an n type material is doped, silicon is doped; it is p. And we know that when p-n junction is formed, a depletion layer is formed, we shall discuss this depletion layer in our earlier lectures also, like this there will be diffusion of the charge carriers from one side to another.

So, holes which are the majority carriers in the p-type silicon, they will move from p side to the n side, and electrons which are majority carriers in the n-type region, they can mover form the n side to p side region. So, there will be diffusion of charges from one side to another side, now when there will be diffusion of charges from one side to another side what will be there, at the region and of the boundary, in the vicinity of the boundary we will find that this is the metallurgical junction.

So, in the very near to the metallurgical junction, we will find that there will be the uncovered charges on both sides of the metallurgical junction, there will be uncovered charges on both sides of the metallurgical junction. So, this uncovered charges they will form, and a built in potential, because this uncovered charges will give rise to an electric field and this electric field, will be directed from the n side to the p side. So that means from positive ions to the negative ions regions, and then this electric field will stop further movement of the charge carriers from the one side to the other side.

So, we know that if this is a p type and this is an n type material. So, if we join. So, there will be this kind of this kind of a bend structure, this is say the Fermi level will align. So, this is n, this is p and this is the Fermi level, throughout the material there will be single Fermi level, and then this is the built in potential, which is denoted by V b i unless such a circumstance the electrons, will not be able to move from the n region to the p region not possible without any kind of application of the bias or the voltage.

So, that thermal equilibrium, when we are not using any bias or the voltage, there will be built in potential, and which will be faced by the charge carriers moving from n region to p region. Now, this is the depletion region, and this depletion region actually is the this region, and in the depletion region, there will be depleted of weak areas. So, there will be almost no carriers in the depletion region.

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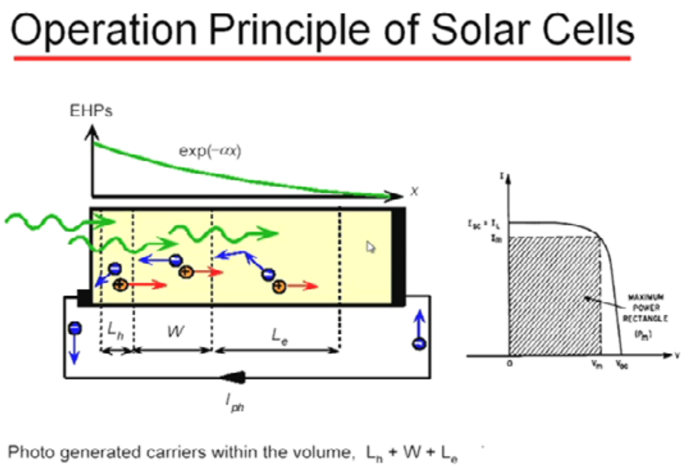

Operation Principle of Solar Cells

Photo generated carriers within the volume, $L_h + W + L_e$

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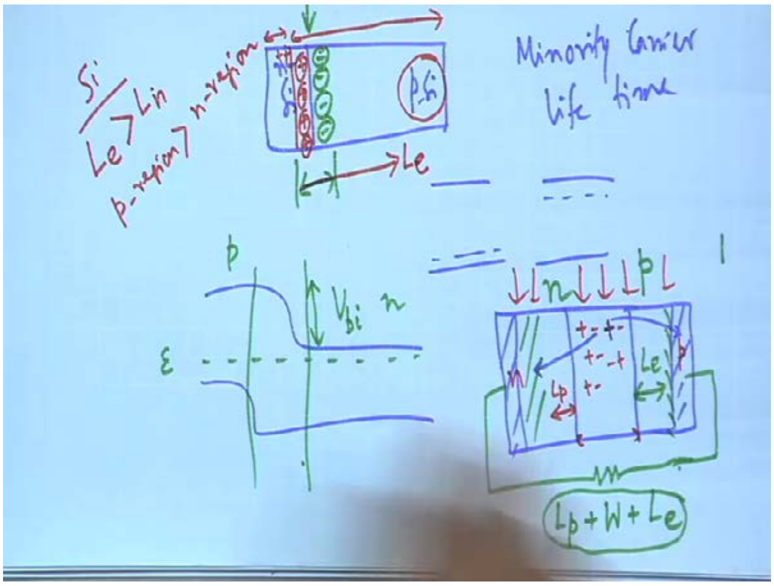

Now, when the solar radiation falls on such kind of a depletion region, when solar radiation falls on will fall on such kind of a depletion region. So, what will happen this is the depletion region you see, and electrons and hole pairs will be created, now electrons and hole pairs will be created, then the then the electric field inside the depletion region, they will separate it will separate electrons and holes. And the electrons will move towards the left or the n region, and the holes will moved from the towards the right of the p region, it is like this, say this is the depletion region, and electrons and hole pairs are created here, there are large number of electrons and hole pairs are created.

It is created out of the solar radiation falling on the solar cell, say this is n side and this is p side, since there is an electric field in the depletion region, this is the depletion region. So, because of the electric field we will find that, the will be drifted, or the electrons will move towards to the n side, and holes will move towards the p side so; that means, p is already the positive terminal, and it has excess number of holes.

So, when positive charge will flow towards the p region, so it will be more positive and when electron will flow towards the n region it will be more negative. So, thereby we will find that 2 electrons have developed, and if you add a load here, so the it will drop power from the cell. So, this is the concept of the solar cell, it is basically physics behind the solar cell, that the solar radiation will fall on the p-n junction, particularly on the depletion region the electrons and whole pairs will be created, and they will be separated.

Now, one concept that we must learn here is the minority carrier life time, it is the minority carrier life time, and this minority carrier life time is an important parameter in case of the solar cell, this is p region, this region we have discussed earlier that this is p region, this is n region, now on the p region, the minority carrier are the electron minority carrier are the electron and this minority carrier life time is that before recombination the electron, how long it can travel. So, that is the minority carrier length, and or the how much how long time it can be as a minority carrier before recombination.

So, that is the minority carrier life time, so depending upon the minority carrier life time, it will travel a minority carrier length; that means, say L e is the minority carrier length similarly, here there will be minority carrier is the hole. So, L p is the minority carrier length, that will move that will move, before it the recombination, so that means the distance, which can be taken into account as L p, the minority carrier diffusion length on the n region plus, the depletion region W plus the minority carrier diffusion length on the p side; that means, of the electron. So, this is the region of interest, where any kind of electron and hole formation by the radiation solar radiation, we can separate the electrons and holes very conveniently. That means, if within the minority carrier diffusion length, the electron and hole pairs are formed, then the electrons will be first diffuse to the depletion region, and in the depletion region they will be drifted to the other side, where it is the majority carrier.

Similarly, the holes which are produced within L p or the minority carrier diffusion length on n side, that will be first diffused to the depletion region, and at the depletion region they will be depleted they will be drifted to the other side. That means, the p side so; that means, any electrons and holes, which are produced within this volume L p plus W plus L e cab be continently and separated, the electrons and holes are separated, and they can reach to the proper are side to make the voltage or the current drawn out of the solar cell is reasonable or possible.

So; that means, not all electrons and holes will be separated or all the holes and electrons can be made to drift to the other side, it is not possible, because apart from L e and L p there is the bulk region, and in this bulk region you can see that there will be recombination. So n side or p side which one will be thick or which one will be thin that will be guided by the minority carrier life time or minority carrier diffusion length, in case of silicon, in case of silicon L e or the minority carrier diffusion length, electron on the p side basically, it is greater than the minority carrier diffusion length of the hole.

So; that means, this L e is greater than L p or L n, so that means we can say that the p region will be greater than the n region. So in the general structure of p-n junction solar cell, we can find that generally a p type material is used, very thinly doped very low doped, and very heavy doped n plus region is made to diffuse at the top of the p silicon. So, this is very small region and this is very large region. So, that we want that the depletion region is formed on the p side, because we know that the region where the electron concentration or the hole concentration carrier concentration is low, on that region there will be the diffusion, there will be the extension of the depletion region.

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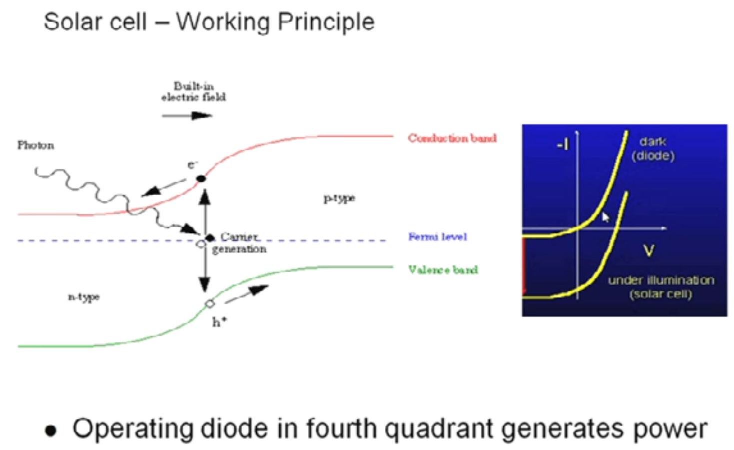

Solar cell – Working Principle

- Operating diode in fourth quadrant generates power

So, here since the doping concentration on the p side is less. So, the depletion region will be more extended towards the p region. So, maximum number of electrons and whole pairs created on the p side, as well as the minority carrier diffusion length, say this is the L e. So, that will be separated the otherwise there will be the recombination of the charge carriers. So, this is the minority carrier diffusion length very important concept in case of the solar cell, and here you see that when I and V is measured with respect to some load connected through the p-n junction solar cell, the dark current is basically the rectifying current without any solar radiation.

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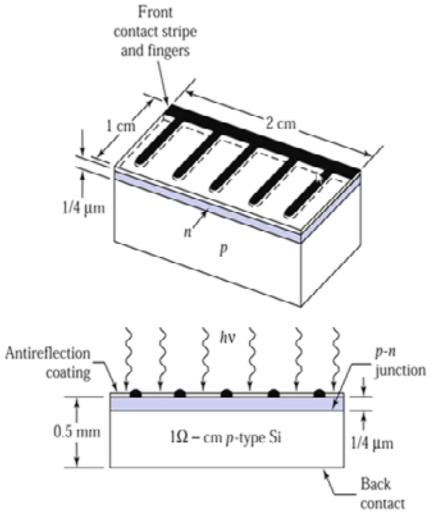
Schematic representation of a silicon *p-n* junction solar cell.

But when there is a solar radiation, we can find that, there will be an increase in current and voltage so this is this is the solar cell operation, in case of any kind of material particularly, we have made use of the p-n junction. Here we see that the top of the cell, there is finger electrodes, here the finger electrodes is very important because we want that most of the solar radiation is passed, through the surface and made to fall inside the material to generate the electrons and holes.

However at the same time, we need to collect the them; that means the we must have some current and voltage obtained from the cell. So, the finger electrodes is used you cannot cover the whole surface in that case the solar radiation, will not be able to pass through the top surface, because light will fall through this surface, at the same time this cannot be made very thin, because in that case the series resistance will increase, we know that the series resistance is important parameter in case of the solar cell. And when we shall discuss about the maximum power rectangle, we will find that the it is a function of the series resistance, depending on the series resistance the rectangle will move towards the ideal situation.

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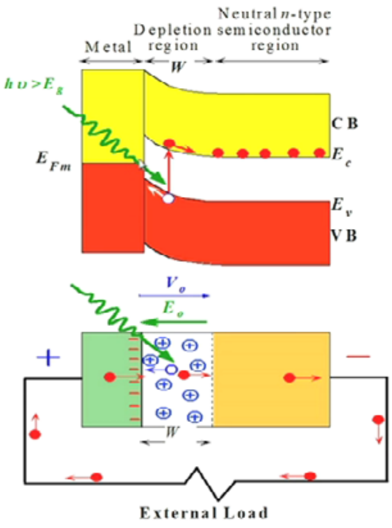

Schottky junction solar cell

Now, another type of concept, which can be made to work is the schottky junction solar cell here, we see that an n type material is taken say silicon, and on the top of it a metal is whose work function is greater than that of the semiconductor work function. Then there will be a depletion region very near to the metal semiconductor junction, this depletion region which is shown on the figure, and as usual we will when solar radiation will fall on the depletion region the electron and hole will be generated, and electron will move towards the semiconductor side and hole towards the metal side. So, when the hole will move towards the metal side, the metal will be less positive, because there are innumerable electrons on the metal side and when holes move.

So, electrons will be recombined with this hole, so it will be moving towards the positive and this will make the n type semiconductor as negative. So, we will find two types of electrode, one is the positive electrode, another is the negative electrode, this is the negative electrode and, when external load is connected the current can be flow through the external load.

So, that is schottky junction solar cell, the importance of schottky junction solar cell is that, we can have many types of materials, where the p-n junction formation is not possible, because of then on stoichiometry, and there will be compensation you cannot make a both type doping possible. And at the same time there can be light, which is less than the band gap generally in p-n junction solar cell, as we have discussed earlier that the band gap will be greater than equals to the or other way, the solar radiation we have the energy greater than or equals to the band gap of the material.

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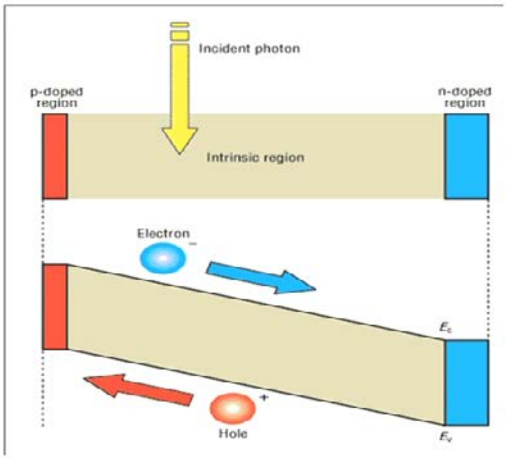
p-i-n solar cell



So, if the material is such that the solar radiation is less energy falling on it, compared to its band gap then what will happen that this can be an absorbed on the metal, and some of the electrons can be made to cross the barrier, so though it is a neglected amount you we can neglect that thing, but the process will be there some electrons will move from the metal to the depletion, through the depletion measure region to the n type. So, making the current larger, another concept is the p-i-n solar cell, we know that in p-i-n solar cell what happens that in p-n junction, we have made the depletion region, though large but in p-i-n junction, we can make this n is region, p region between n and p there is un doped this is un doped or intrinsic n region.

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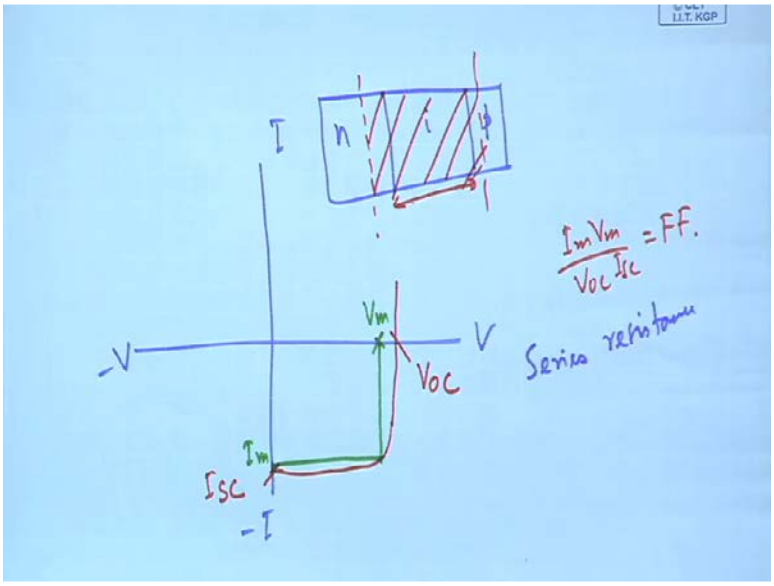

So, this is un doped or intrinsic n region, this is p-n. So, when so what will happen that when we join this type of a structure p-i-n, when we make this kind of a structure, this will be fully depleted region, there will be depletion region say starting from here, to here. So, completely i region will be fully depleted region. So, we can make use the depletion region, large depletion region to separate the electrons and holes, which are formed on the material.

So, different kind of structure has been evolved, slowly to obtain the depletion region or the electric field inside the depletion region more. So, that it can be possible to separate the electrons and holes, which are generated on the depletion region. So we find that there are different types of structures and if we draw, the fourth quadrant response of this current and voltage, we will find that there will be the characterisation will look like this.

So, this point is known as the open circuit voltage, and this will be known as short circuit current, so this is two important parameter of the open circuit voltage, and short circuit current, and this is the maximum power rectangle; that means one can optimise this rectangle. So, it can be like this maximum rectangle. So, this is the maximum voltage that can be drawn from the solar cell, and that is the maximum current that can be drawn from the solar cell; that means, the load can draw, and this I m V m by V o c I s c this parameter is known as the fill factor, this fill factor is denotes that how this maximum power rectangle is closed to the characteristics, or the characteristics is close to the maximum power rectangle.

So, when both are equal the fill factor will be 100 percent almost, but we see that I m V m product will always be less than V o c I s c and. So, the fill factor is always less than 100 percent in normal cases, it can be seventy to 80 percent, and to achieve very good kind of characteristics of the solar cell, another important thing that we must discuss is the series resistance, effect of series resistance. The series resistance comes from this finger electrodes, we see and there are other possibilities like, the doping concentration depending on the metal between, the metal and the semiconductor.

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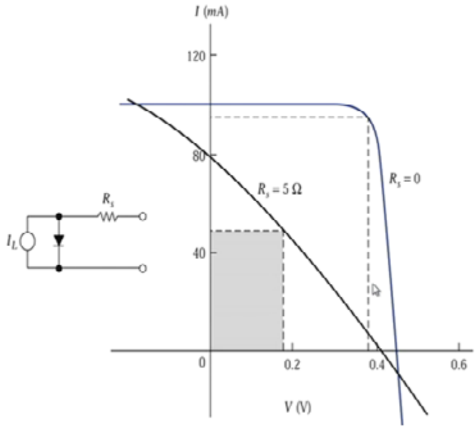

Current-voltage characteristics and the equivalent circuit of solar cells that have resistances.

So, series resistance is very important parameter in case of the solar cell, we see that when the series resistance is 0, it is assuming almost rectangular characteristics, this blue one but when there is a series resistance, say 5 ohms, series resistance is there this blue curve comes down to as to this line; that means, it is basically very small rectangle, which can be obtained out of this characteristics. So, as the series resistance increases the maximum power rectangle becomes less, so that means, the efficiency will be very less so we find that the efficiency is a function of the maximum power rectangle, and obviously this is also a function of the series resistance.

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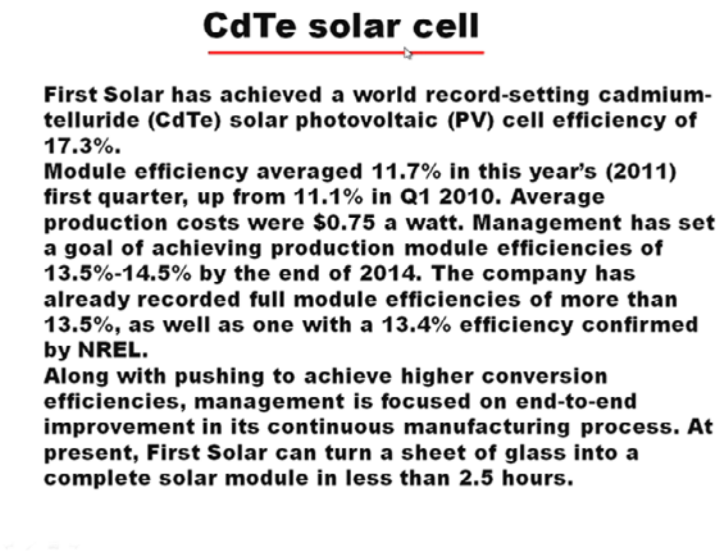

CdTe solar cell

First Solar has achieved a world record-setting cadmium-telluride (CdTe) solar photovoltaic (PV) cell efficiency of 17.3%.
Module efficiency averaged 11.7% in this year's (2011) first quarter, up from 11.1% in Q1 2010. Average production costs were \$0.75 a watt. Management has set a goal of achieving production module efficiencies of 13.5%-14.5% by the end of 2014. The company has already recorded full module efficiencies of more than 13.5%, as well as one with a 13.4% efficiency confirmed by NREL.
Along with pushing to achieve higher conversion efficiencies, management is focused on end-to-end improvement in its continuous manufacturing process. At present, First Solar can turn a sheet of glass into a complete solar module in less than 2.5 hours.

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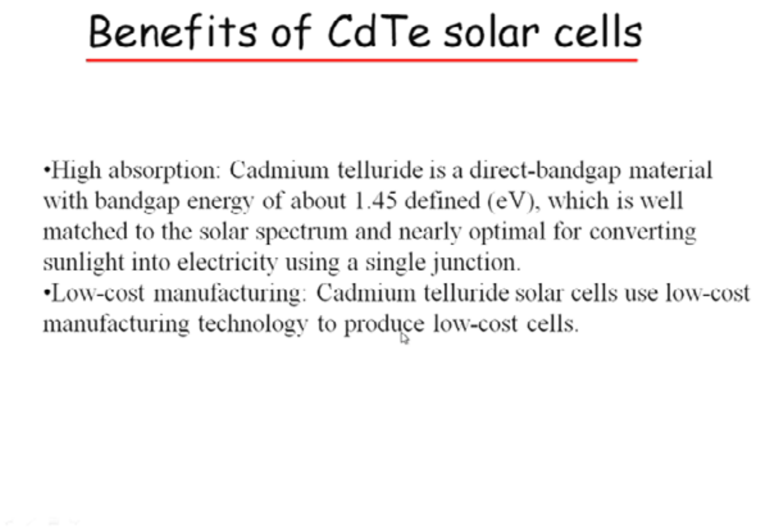

Benefits of CdTe solar cells

•High absorption: Cadmium telluride is a direct-bandgap material with bandgap energy of about 1.45 defined (eV), which is well matched to the solar spectrum and nearly optimal for converting sunlight into electricity using a single junction.
•Low-cost manufacturing: Cadmium telluride solar cells use low-cost manufacturing technology to produce low-cost cells.

So, the idea is that we have to minimise the series resistance by different types of processes, which we can adopt. Now with this discussion that this is mostly pertinent to the silicon, and what happens when different types of thin film materials, we will use say in case of this in case of say different types of material, which we make use say let us, consider first is cadmium telluride, let us first concentrate our discussion on the cadmium telluride solar cell. And here we see that different types can be different types of structures can be made we shall show you, it has high absorption it is high absorption, cadmium telluride is a direct band gap material with high band gap energy of about 1.45

electron volt, which is well matched to the solar spectrum, and nearly optimal for converting sunlight into electricity using a single junction.

And low manufacturing cost, why because cadmium telluride solar cells is low cost manufacturing technology to produce low-cost cell, low cost manufacturing technology means, that it is a thin film technology, not the bulk crystal growth in involved. However, the problem is with the cadmium telluride is that tellurium availability on this very less which is 0.01 p p m and cadmium is toxic.

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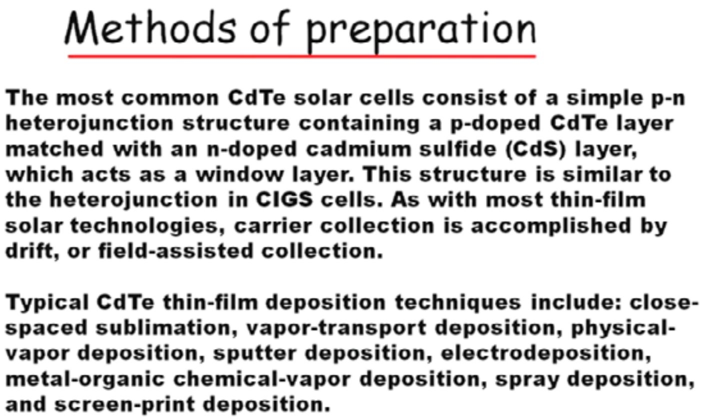

Methods of preparation

The most common CdTe solar cells consist of a simple p-n heterojunction structure containing a p-doped CdTe layer matched with an n-doped cadmium sulfide (CdS) layer, which acts as a window layer. This structure is similar to the heterojunction in CIGS cells. As with most thin-film solar technologies, carrier collection is accomplished by drift, or field-assisted collection.

Typical CdTe thin-film deposition techniques include: close-spaced sublimation, vapor-transport deposition, physical-vapor deposition, sputter deposition, electrodeposition, metal-organic chemical-vapor deposition, spray deposition, and screen-print deposition.

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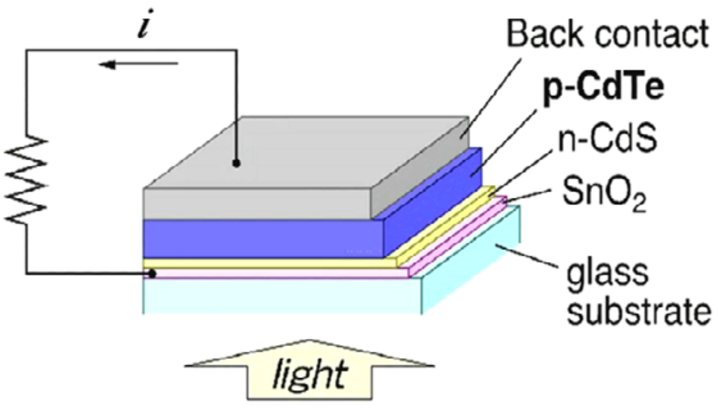

So it is very important to consider the other type of materials, so here we can see that the structure is like this let us take a glass substrate, on the glass substrate the tin oxide is deposited, tin oxide is the transparent conducting oxide, and then the p-n hetero junction is made.

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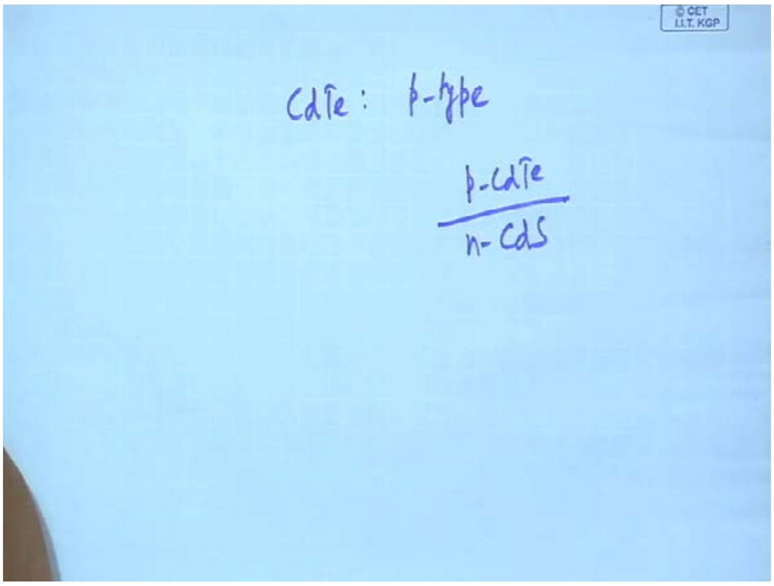

It is important to discuss here, that cadmium telluride is p type material, it is a p type material. So, what happens that you have to make use of the hetero junction, so generally this p cadmium telluride and n cadmium sulphate, so junction between two dissimilar semiconductor you can see that this p cadmium telluride and n cadmium celluloid cadmium sulphide, it is used as a hetero junction between the two material and then there is a back contact.

Now, solar radiation falls on through this glass substrate to obtain the electron hole pair formed of the p cadmium telluride, this cadmium sulphide is basically the window layer here with higher band gap and tin oxide is the transparent conducting oxide. So, when the electron and hole pairs are generated on this emitter p cadmium telluride, at the electric field produced at the hetero junction depletion region between 2 p-n–n junctions, what happens they separate the electrons and hole pairs and we can will get a photocurrent, which can be drawn using a load.

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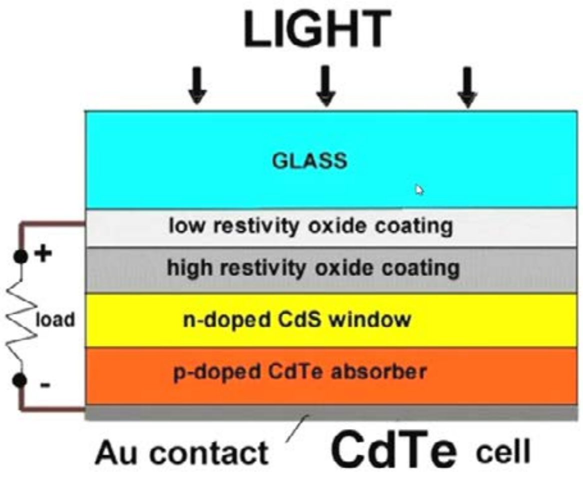

Similar structure can be like this say this is glass substrate, now this glass substrate is used as a super state on the glass substrate low resistivity oxides coating, and high resistivity oxides coating is done generally. This is tin oxide first one and the second one is the intrinsic zinc oxide, then the n-doped C d s window, that is the window layer and p-doped cadmium telluride absorber, at the back contact there is a gold contact, because between two contact two electrodes we shall connect the load.

So, different type of structure is used and you can see that it has the flexibility to be grown on the glass, it has the flexibility to make use of a particular semiconductor in this case the cadmium telluride emitter, and it has the higher absorption coefficient. However, the 14 percent, 15 percent or maximum 17 percent is the efficiency reported for this kind of a solar cell.

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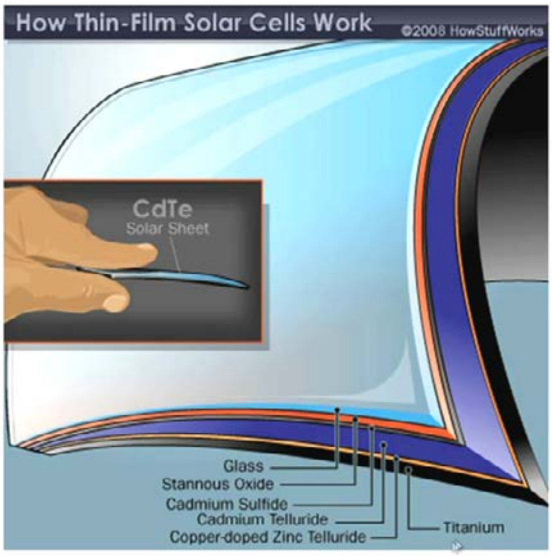

Here we can make use of the flexible substrate also, you can see that this is flexible substrate, and on the flexible substrate that this structure is used.

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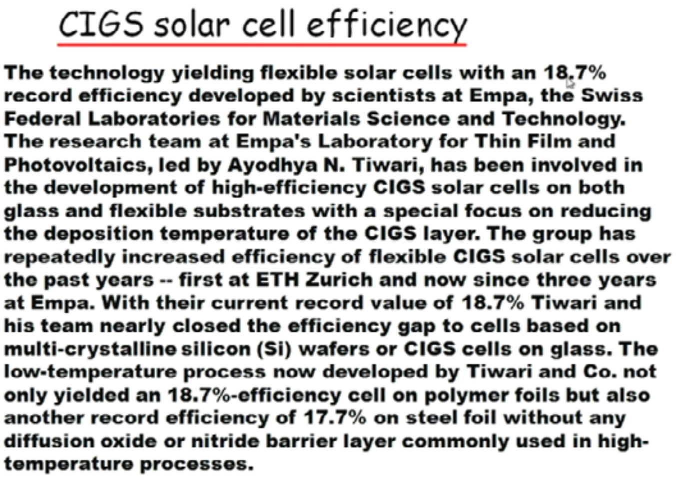

CIGS solar cell efficiency

The technology yielding flexible solar cells with an 18.7% record efficiency developed by scientists at Empa, the Swiss Federal Laboratories for Materials Science and Technology. The research team at Empa's Laboratory for Thin Film and Photovoltaics, led by Ayodhya N. Tiwari, has been involved in the development of high-efficiency CIGS solar cells on both glass and flexible substrates with a special focus on reducing the deposition temperature of the CIGS layer. The group has repeatedly increased efficiency of flexible CIGS solar cells over the past years -- first at ETH Zurich and now since three years at Empa. With their current record value of 18.7% Tiwari and his team nearly closed the efficiency gap to cells based on multi-crystalline silicon (Si) wafers or CIGS cells on glass. The low-temperature process now developed by Tiwari and Co. not only yielded an 18.7%-efficiency cell on polymer foils but also another record efficiency of 17.7% on steel foil without any diffusion oxide or nitride barrier layer commonly used in high-temperature processes.

Another material can be the copper indium gallium solenoid C I G S, and it is almost 18.7 percent has been obtained, you can see that 18.7 percent efficiency is obtained.

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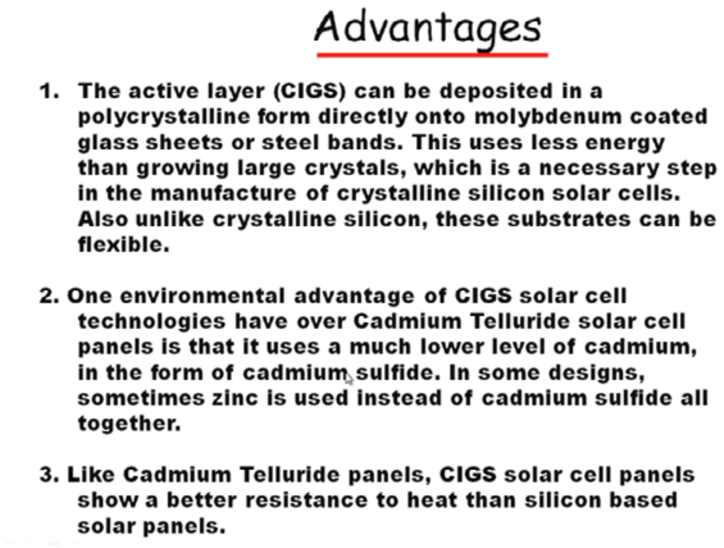

Advantages

1. **The active layer (CIGS) can be deposited in a polycrystalline form directly onto molybdenum coated glass sheets or steel bands. This uses less energy than growing large crystals, which is a necessary step in the manufacture of crystalline silicon solar cells. Also unlike crystalline silicon, these substrates can be flexible.**
2. **One environmental advantage of CIGS solar cell technologies have over Cadmium Telluride solar cell panels is that it uses a much lower level of cadmium, in the form of cadmium sulfide. In some designs, sometimes zinc is used instead of cadmium sulfide all together.**
3. **Like Cadmium Telluride panels, CIGS solar cell panels show a better resistance to heat than silicon based solar panels.**

It has advantage, it has some advantages like this, the active layer or the emitter can be deposited in a polycrystalline form, directly onto molybdenum coated glass sheets or steel bands. So, this is important that, we can make use of the flexible substrate, this uses less energy than growing large crystals, which is necessary step in the manufacture of crystalline silicon solar cells, so a large crystals we cannot use, we were not using, so less energy is involved also unlike silicon crystalline silicon, this substrates can be flexible.

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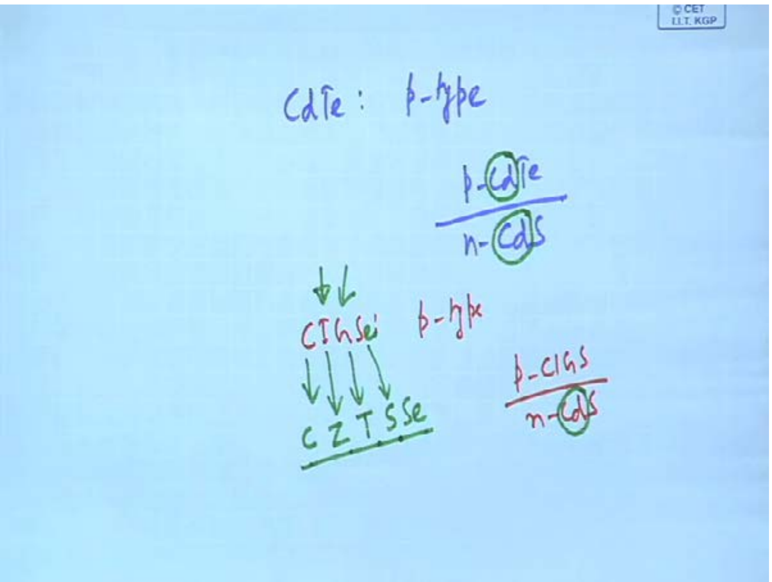

So, that is first advantage, second thing is that one environmental advantage of C I G S solar technology is over cadmium telluride solar cell panels is that, it uses a much lower level of cadmium, in the form of cadmium sulphide as earlier. We can show you that the structure of this C I G S copper indium gallium solenoid, it is also a p type material. So, the structure will be p cadmium p-C I G S and then n-C d s. So, here cadmium will be involved as a cadmium in cadmium telluride, and cadmium in cadmium sulphide here, for the basic material; that means, for the emitter region no cadmium is involved, only cadmium is used in the window material C d s.

So, less amount of c d cadmium is used, in some design sometimes zinc is used instead of cadmium sulphide all together. That means, here this copper in instead of indium we can use zinc, in case of gallium we can use T or the tin and this selenium we can use sulphur, and then selenium; that means this is selenium, and the selenium is replaced by sulphur to some amount.

So, what is the region for change in this material, the reason is that indium is availability indium availability is very, very small, and zinc is largely available similarly, gallium is costly, and we can use the tin is less costly. And in case of selenium we can use this sulphur, which is readily available, so basically, so far as the cost is concerned. So, far as the also we had we can change this system from that cadmium containing material, cadmium is toxic indium is costly, because of the non availability.

So, all such things we can move tellurium is also availability is very less. So, different type of materials, we can replace to obtain C Z T S; that means, the copper zinc tin sulphur instead of C I G S or the copper indium gallium solenoid, and like cadmium telluride panels C I G S solar cell panel show a better resistance to heat, then silicon based solar panels.

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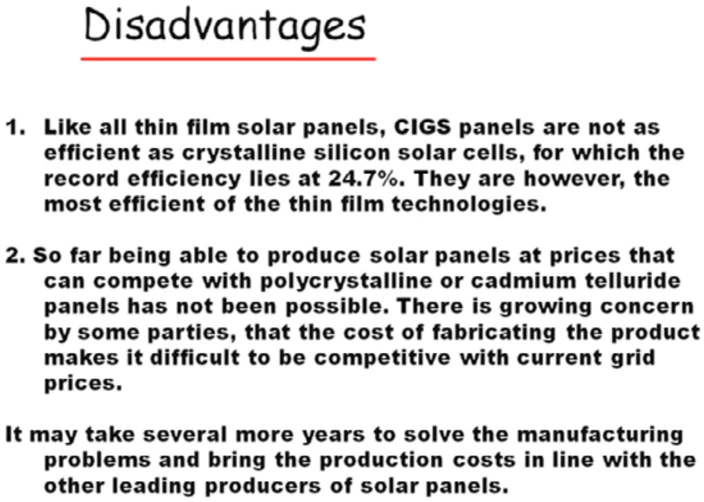

Disadvantages

1. Like all thin film solar panels, CIGS panels are not as efficient as crystalline silicon solar cells, for which the record efficiency lies at 24.7%. They are however, the most efficient of the thin film technologies.
2. So far being able to produce solar panels at prices that can compete with polycrystalline or cadmium telluride panels has not been possible. There is growing concern by some parties, that the cost of fabricating the product makes it difficult to be competitive with current grid prices.

It may take several more years to solve the manufacturing problems and bring the production costs in line with the other leading producers of solar panels.

It has some disadvantage as well like all thin film solar panels, C I G S panels are not as efficient as crystalline silicon solar cells, for which the record efficiency lies at 24.7 percent, this 24.7 percent is for silicon. In C I G S, it is 18.7 percent, so far as the efficiency concerned you can see that not efficient there are; however, most efficient of the thin film technologies, if you consider that thin film technology, like with amorphous silicon or with c d T e, they have the highest because you know that for c d T e, the efficiency is almost 7.7 percent, and module efficiency but cell efficiency is 17.3 percent.

So, if you consider that if it is 17.3 percent, it is 18.7 percent, and silicon is 24.7 percent, so it is not that efficiency like the solar silicon solar cell, so far being able to produce solar panels at prices that can compete with polycrystalline or cadmium telluride panels has not been possible. There is growing concern by some parties, that cost of fabricating the product, makes it difficult to be competitive with current grid prices, current grid prices is some say less than a dollar per watt, and it may take several more years to manufacturing problems, and bring the production cost in line with the other leading producers of solar panels.

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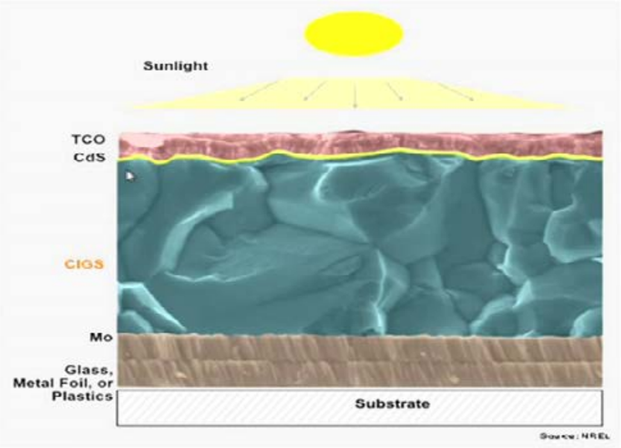

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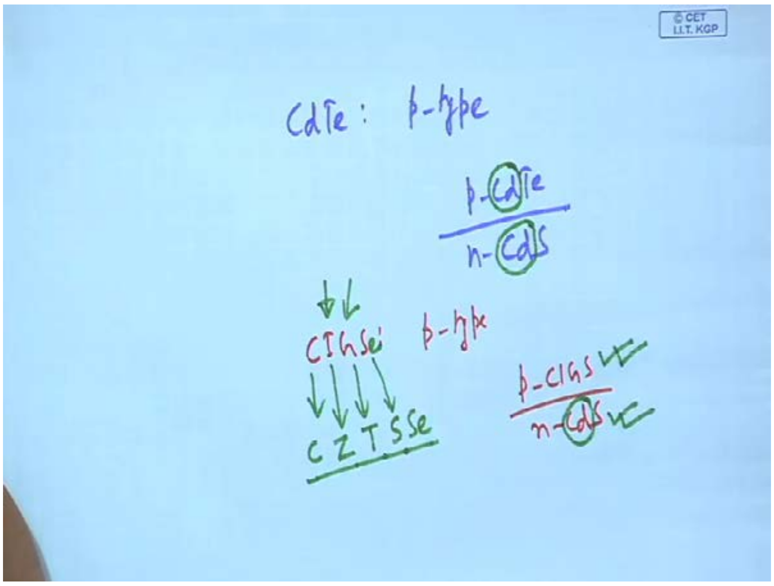

So, it has some advantage, it has some disadvantage, as well and you see that this is the polycrystalline material, which is used. So, you take a substrate say plastic, glass or metal foil on which you can deposit molybdenum, on the molybdenum directly the C I G S can be deposited, on which this yellow line is basically C d s, cadmium sulphide because we have discussed earlier that, in this case the p type C I G S, you see p type C I G S, and n type C d s.

The junction between the two is the disjunction, and above c d s there is a transparent conducting oxide, which can be tin oxide, which can be zinc oxide etcetera, through which the solar radiation enters the material.

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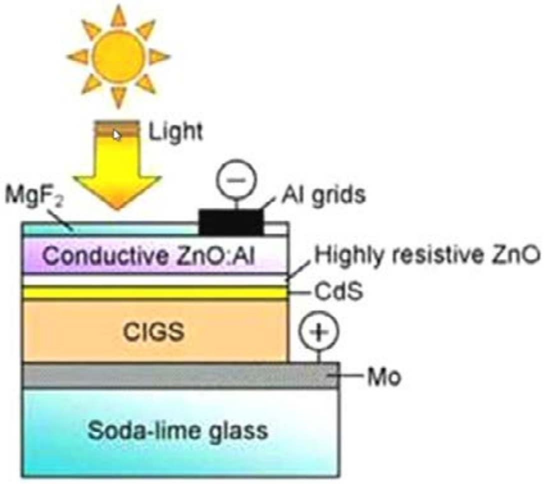

So this is a the structure, as shown earlier this is let us take a soda lime glass on, which the molybdenum coating is used, and then the copper indium gallium solenoid C I G S, then C d s. So, this is the p-n junction, in fact, it is a hetero junction, then highly resistive zinc oxide and conducting aluminium doped zinc oxide, these are very cheap material on inexpensive material.

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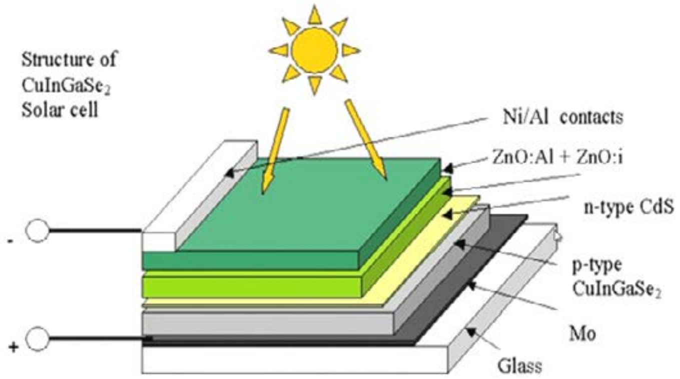

Then the coating is used M g F 2, that the antireflection coating. So, we find that the structure is more or less same, here also the same structure. This p type material and n type material c d s is used. So, the advantage of this kind of a thin film solar cell is that, you can make use of the flexible structures, made of glass or some foil metal foil or plastic that is important, but it must be competitive as well.

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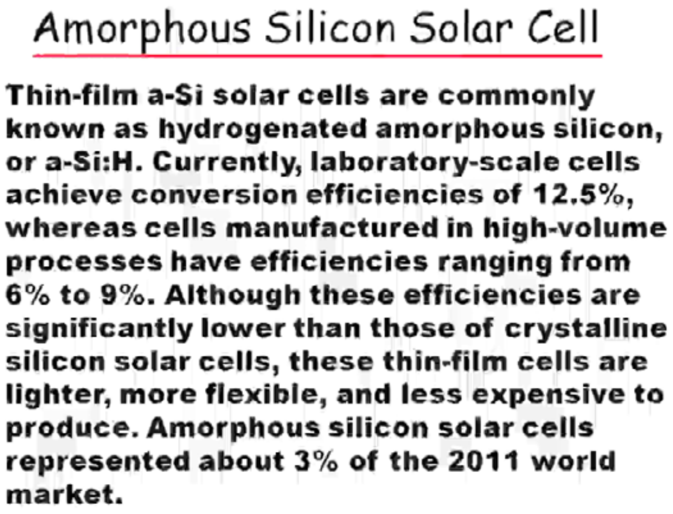

Amorphous Silicon Solar Cell

Thin-film a-Si solar cells are commonly known as hydrogenated amorphous silicon, or a-Si:H. Currently, laboratory-scale cells achieve conversion efficiencies of 12.5%, whereas cells manufactured in high-volume processes have efficiencies ranging from 6% to 9%. Although these efficiencies are significantly lower than those of crystalline silicon solar cells, these thin-film cells are lighter, more flexible, and less expensive to produce. Amorphous silicon solar cells represented about 3% of the 2011 world market.

Then another thin film material is the amorphous silicon solar cell, because at the beginning we have discussed that there are other materials also but… So, far as this p-n junction is concerned, we can see that. So, far as this p-n junction is concerned. This is silicon but silicon can be of 3 types we have discussed earlier. So, let us now concentrate on this amorphous silicon solar cell, we know that in case of amorphous silicon no defined band gap is there, only band tail is available. And there is a number of surface states or tails states, available inside the material amorphous silicon, because of the unsaturated dangling bonds because of this amorphous nature there is no crystalline structure.

So, no long or short range or potential is available in case of amorphous silicon solar cell, amorphous silicon material. And this band gap is 1.12, it is basically greater than 1.12, and the for the for that reason, it is very suitable and at that band gap at that, and the material is basically having very good absorption coefficient, thin film amorphous silicon solar cells are commonly known as hydrogenated amorphous silicon solar silicon or amorphous silicon hydrogenated.

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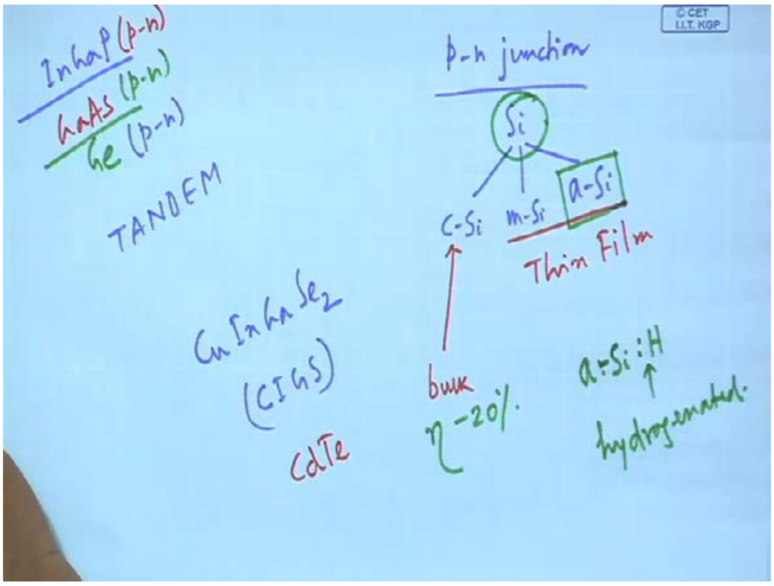

Why it is made? Because to saturate the dangling bond, this is the amorphous silicon, and then colon h this means that, it is hydrogenated, it is hydrogenated and this hydrogenated, means it is the dangling bonds are saturated. So, that some of the property, like the mobility etcetera, can be enhanced some defects can be controlled currently laboratory scale cells achieve conversion efficiencies of 12.5 percent whereas, cells manufactured in high volume processes have efficiencies ranging from 6 to 9 percent.

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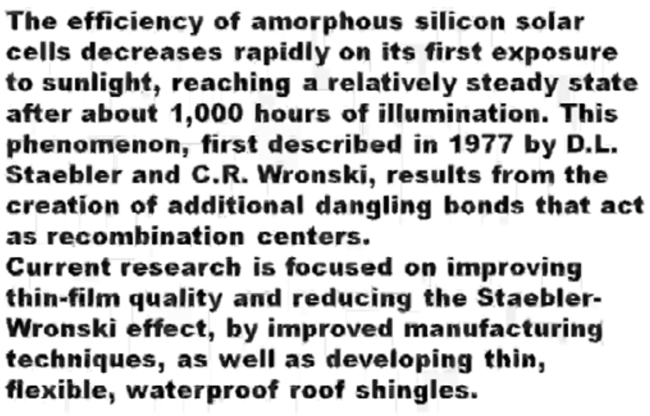

The efficiency of amorphous silicon solar cells decreases rapidly on its first exposure to sunlight, reaching a relatively steady state after about 1,000 hours of illumination. This phenomenon, first described in 1977 by D.L. Staebler and C.R. Wronski, results from the creation of additional dangling bonds that act as recombination centers.

Current research is focused on improving thin-film quality and reducing the Staebler-Wronski effect, by improved manufacturing techniques, as well as developing thin, flexible, waterproof roof shingles.

Although these efficiencies are significantly lower than those of crystalline silicon solar cells, these thin films are lighter more flexible, and less expensive to produce amorphous silicon solar cells represented about 3 percent of the 2011 world market. So, that is important that, it has gaining, its strength it is gaining its momentum to enter in to the world market the efficiency of amorphous silicon solar cell decreases rapidly, on its first exposure to sunlight reaching a relatively steady state, after about 1000 hours of illumination, this phenomenon was described in 1977 by Staebler and Wronski results from the creation of additional dangling bonds, that act as recombination centres.

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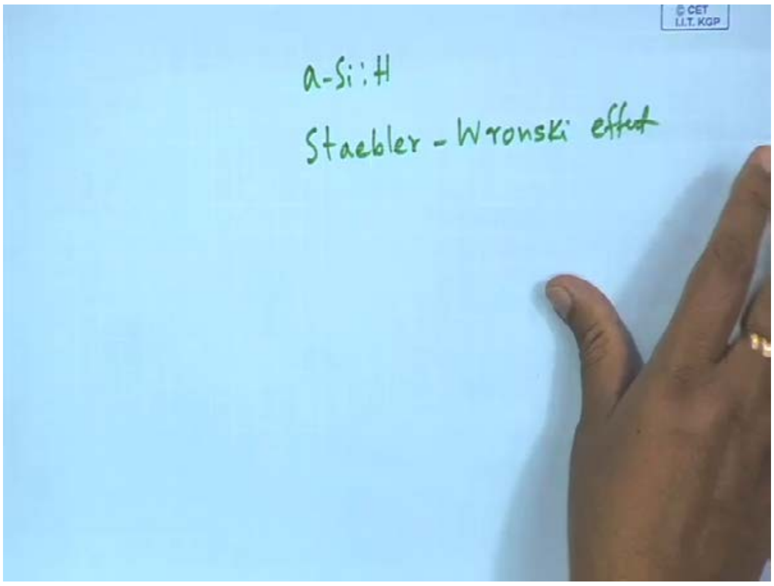

a-Si:H

Staebler - Wronski effect

So, what happens? This is very important phenomena, in case of that amorphous silicon solar cell, in case of amorphous silicon solar cell the problem is staebler wronski effect stabler Staebler Wronski wronski, this staebler wronski effect is the effect that within the first 1000 hours of illumination, the recombination centre increasing additional dangling bonds increases. So, there is a stable efficiency after 1000 hours of illumination.

So, say if it is 12 percent then after 1000 hours the efficiency can be say 8 percent 9 percent. So, that is very important thing that Staebler Wronski effect, that is the thermal effect thermally degradation of the amorphous silicon material, and within the first 1000 hours of illumination and current research is focused on improving thin film quality, and reducing the stealer wonks effect by improved manufacturing techniques, as well as developing thin flexible waterproof roofs shingles.

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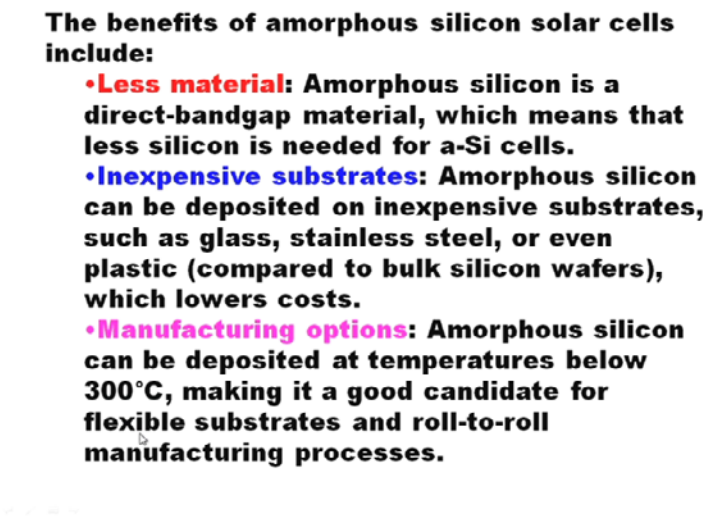

The benefits of amorphous silicon solar cells include:

- **Less material: Amorphous silicon is a direct-bandgap material, which means that less silicon is needed for a-Si cells.**
- **Inexpensive substrates: Amorphous silicon can be deposited on inexpensive substrates, such as glass, stainless steel, or even plastic (compared to bulk silicon wafers), which lowers costs.**
- **Manufacturing options: Amorphous silicon can be deposited at temperatures below 300°C, making it a good candidate for flexible substrates and roll-to-roll manufacturing processes.**

And the benefits of amorphous silicon solar cells include less material, because amorphous silicon is a direct band gap material, which means that less silicon is needed for amorphous silicon cells due to its large coefficient of absorption, inexpensive substrates amorphous silicon can be deposited on inexpensive substrates. Such as glass, stainless steel or even plastic compared to bulk silicon wafers, which lowers the cost.

So, less material due to direct nature of the band gap and thus the higher absorption coefficient inexpensive substrate, and third one is the manufacturing options, amorphous silicon can be deposited at temperatures below 300 degree centigrade making it a good candidate for flexible substrates and roll to roll manufacturing process, because if you make use of the polymer or plastic substrates, higher temperature cannot withstand higher temperature.

So, if you consider the bulk silicon solar cell, the temperature involved is a 1400 almost greater than 1400 degree centigrade, because of the melting point of silicon and in this case it is just 300 degree centigrade, and manufacturing options are very high, roll to roll manufacturing processing is possible.

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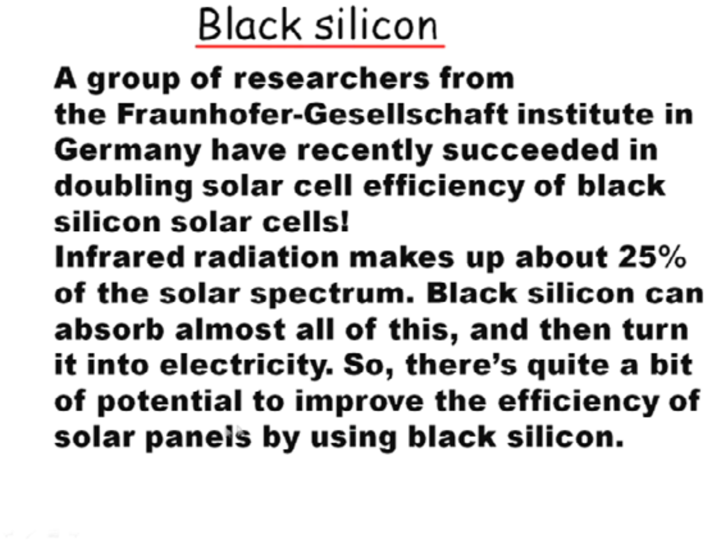

Black silicon

A group of researchers from the Fraunhofer-Gesellschaft institute in Germany have recently succeeded in doubling solar cell efficiency of black silicon solar cells!
Infrared radiation makes up about 25% of the solar spectrum. Black silicon can absorb almost all of this, and then turn it into electricity. So, there’s quite a bit of potential to improve the efficiency of solar panels by using black silicon.

Another thing which is obtained and is known as the black silicon, it is a group of researchers from fraunhofer-gesellschaft institute in Germany, they have recently succeeded in doubling solar cell efficiency of black silicon solar cells. Infrared radiation makes up about 25 percent of the solar spectrum, and even more than that black silicon can absorb almost all of this, and then turn it into electricity. So, there’s quite a bit of potential to improve the efficiency of solar panel by using the black silicon.

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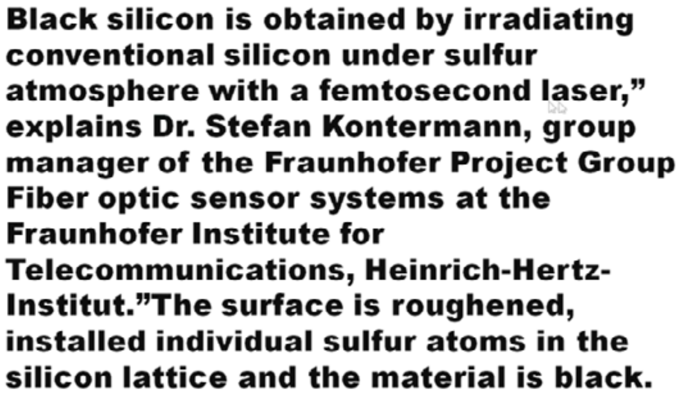

Black silicon is obtained by irradiating conventional silicon under sulfur atmosphere with a femtosecond laser," explains Dr. Stefan Kontermann, group manager of the Fraunhofer Project Group Fiber optic sensor systems at the Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institut."The surface is roughened, installed individual sulfur atoms in the silicon lattice and the material is black.

Now, how it is obtained, it is obtained by eradiating conventional silicon under sulphur atmosphere with a fem to second laser. And you see that the surface is roughened installed individual sulphur atoms in the silicon lattice, and the material becomes black. So, that is the black silicon, this region is magnified here. So, it is the sulphurization basically conventional silicon under sulphur atmosphere with a fem to second laser. So, advantage is that, it can it can absorb this you see that on first some slides, I have shown you, that it can absorbs the infrared some 25 percent infrared it can absorb. So that means, the efficiency can be increase, apart from the absorption of the visible region.

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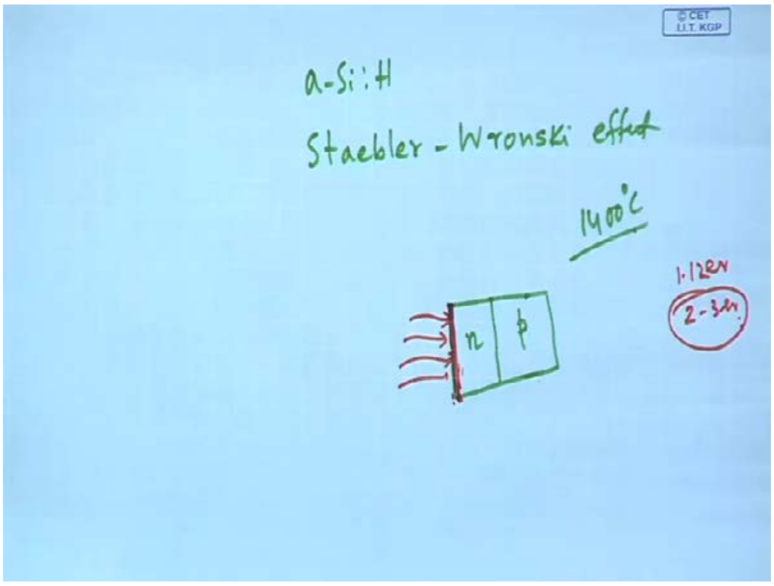

Now, problem with this kind of cell is that though, it is made of very low cost material etcetera but what happens, that in say a p-n junction silicon solar cell. So, let us consider, that high energy light, this high energy light say its band gap is 1.12 electron volt, so 1.12 or around, 1.12 electron volt light it can be absorbed very conveniently. But say around 2.3 electron volt or even greater than this energy, that will be absorbed at the surface, that will be absorbed at the surface high energy radiation an electrons and hole pairs will be created at the surface, and they will not be able to separated or we cannot be able to separate them, and very small energy they cannot penetrate.

So, that is the important thing that small energy cannot be absorbed, because of the band gap restriction and high energy, which are absorbed at the surface are very near to the metal semiconductor junction, they will be lost because the electrons and hole pairs will be created there, and there will be a large number of surface there. So, that makes this material problematic in the sense that not the whole solar radiation, which falls on the material can be harnessed. So, as some new structure or some new kind of material one can consider, and in the next part we shall we can discuss this kind of effect or the materials in details.

Thank you.