Solar Energy Engineering and Technology
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Lecture 09
Solar Photovoltaic

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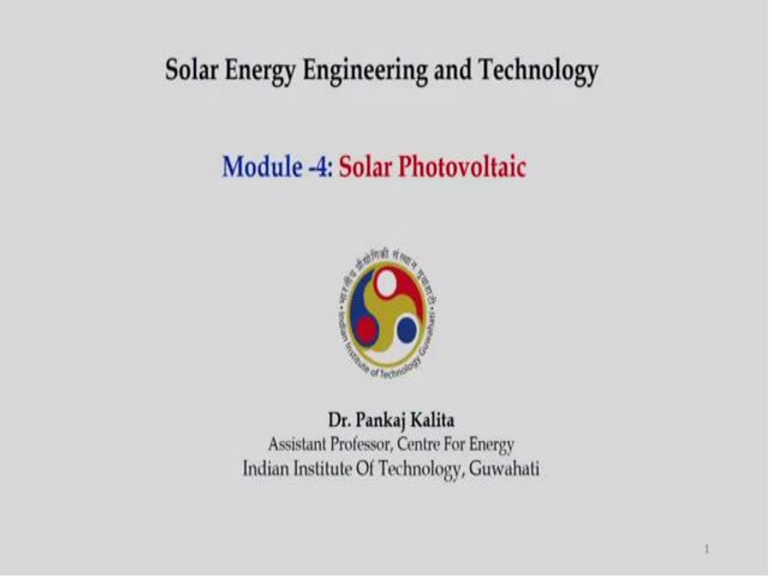

Dear students, today we will be learning solar photovoltaic. Basically, we will include basics of PV cells, its construction, manufacturing processes and working principle of PV conversion.

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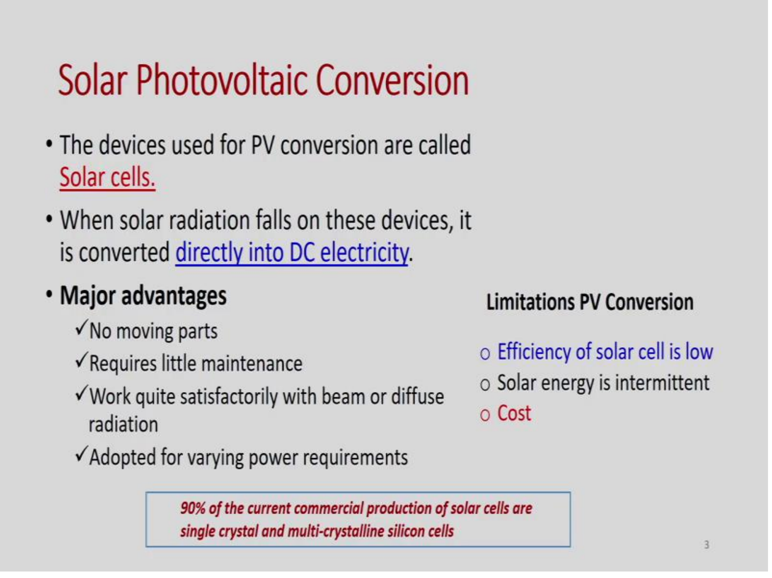

So, let us learn about solar photovoltaic conversion. So, most of the time, we heard the word solar cells. So, what is solar cells? The devices used for PV conversion are called solar cells. When solar radiation falls on these devices, it is converted directly to DC current, DC current means direct current.

So, there are plenty of advantages in using these solar PV technologies. Some of the advantages are no moving part, there is no thermo mechanical conversion, requires little maintenance. Only periodic cleaning is required for sustainability and it work quite satisfactorily with beam or diffused radiation and it is adopted for varying power requirements.

So, we can edit based on our requirement and the primary limitations of this PV technologies are efficiency of the cell is low and solar energy is intermittent. So, we need to depend on some kind of storage systems and cost is an issue. And as we can see for your information, in the market 90% of the solar cells are made of silicon based solar cells. That means, single crystalline and multi crystalline solar cells.

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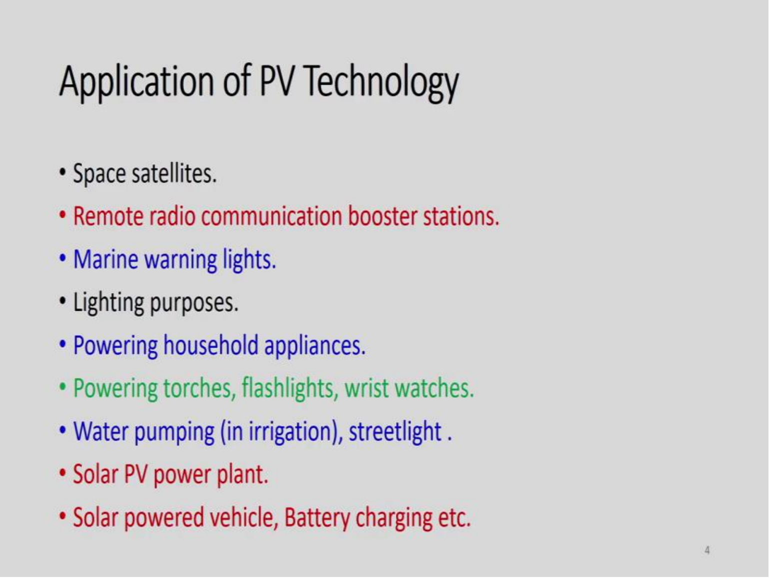

So, let us learn something about their applications, there are multiple applications. So, among all the applications, the prominent applications are space satellites, then remote radio communication booster stations, marine warning lamps, lighting purposes, then powering household applications, then powering torches, flashlight, wrist watches, water pumping in irrigation and street lighting then solar PV power plant for large scale power generation and modern uses are something like, solar powered vehicles, then battery charging stations, which are very, very modern use.

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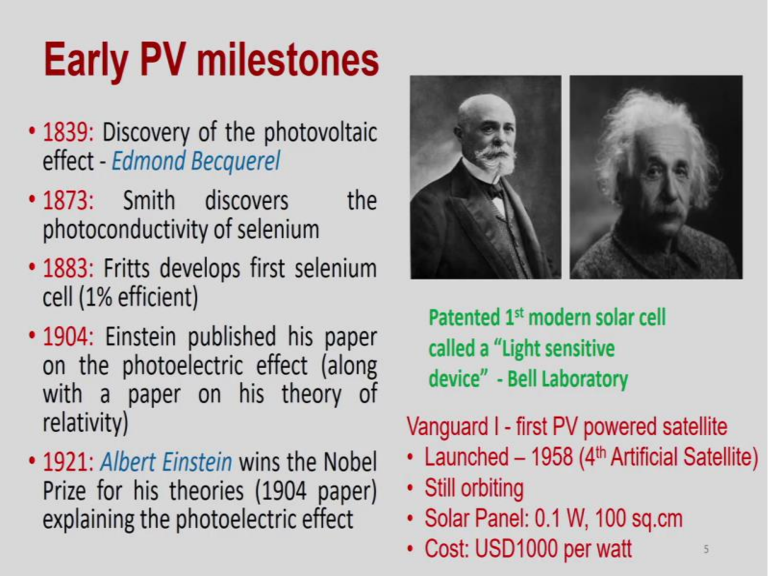

Now, let us learn something on early PV milestones. In 1839, Edmond Becquerel discovered the photovoltaic effect, while experimenting with a electrolytic cell where, he has used two metal electrodes and a electron conducting media. So, what he has observed with exposure to these cells, the rise in current is observed.

And in 1873, Smith discovers the photoconductivity of selenium. Fritts develops first selenium cells having efficiency 1% in 1883. In 1904, Einstein published his first paper on photoelectric effect along with a paper on his theory of relativity. In 1921, Albert Einstein wins the Nobel Prize for his theories explaining the photoelectric effect and this first patent was filed in the year 1950s from Bell Laboratory and that was known as light sensitive devices, which is nothing but modern solar cells.

As for your information, that the first PV powered satellite called Vanguard I still orbiting the earth, which is launched in 1958 and which is the 4th artificial satellite powered by a solar panel having 0.1W an area of 100 cm^2 and cost was very, very high. It was about $1,000 per watt, it was very, very high.

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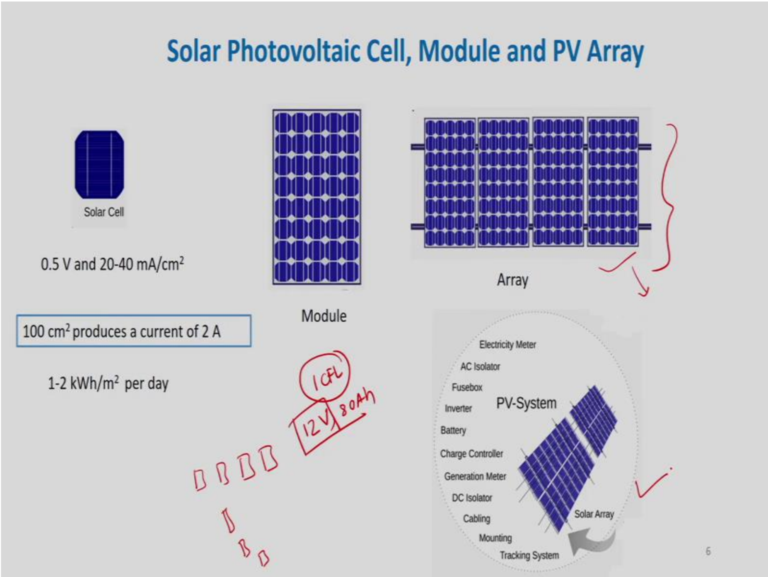

Now, let us see the distinction between cells, modules and arrays. In cells, say for example, if you consider silicon based solar cells, so it can provide a voltage output of 0.5 V and current density of 20 to 40 mA/cm^2. So, for example, if we consider 100 cm^2 is the area, if we multiply with in this current density then, what you will get is the current, which is nothing but 2 A. And also it is said that so, 1 to 2 kWh/m^2-day energy can be generated by using a single solar cell.

So, there are multiple applications of these cells, like in our calculators; these cells are used or maybe watches, these cells are used. So, it is very small one and in case of modules, we will have many cells. These are connected in series and parallel based on our requirements.

So, these modules are used for many of the applications like, say for example, in streetlights. So, in streetlights our requirement maybe 1 cfl, 1 cfl and then if we are using a battery so, battery voltage maybe 12 V or maybe 80 Ah. So, this is something like that, so 12 V batteries. So, in order to power this 12 V battery then we can decide the number of cells to be connected in series.

So, when these cells are connected in series then what we are doing? We are maximising the voltages. When the cells are connected in parallel, then we are maximising the current; that way we can decide. And what is arrays?

So, if we connect many modules that becomes arrays. So, this arrays has multiple applications. So, maybe household applications if we are powering our houses, all the appliances or maybe in irrigations. Suppose one pump will be there to lift water. So, in order to power this pump so we need to rely on this kind of arrays. And if we are interested for large scale power generation then what we need to do? We need to go for PV system, which is very, very large installations.

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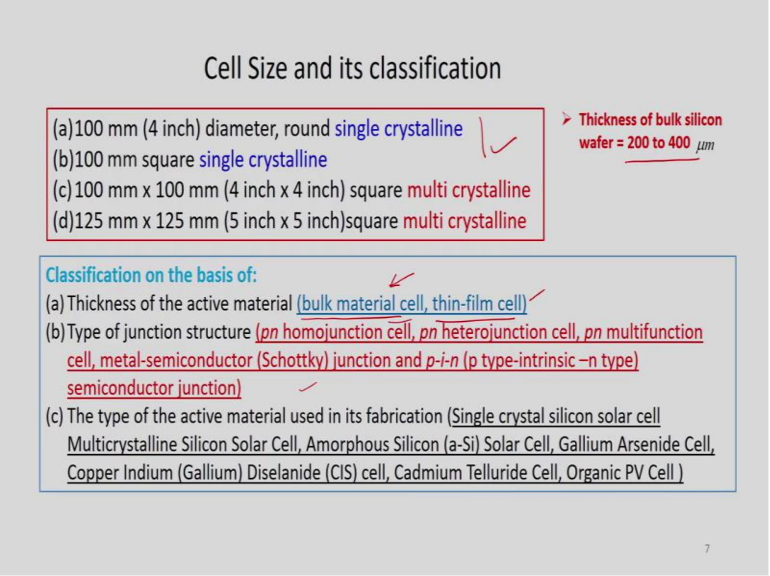

So, let us classify those cell sizes and its different material. So, when we talk about cell sizes, there are industries who actually specify the sizes, because they cannot have very big sizes, because homogeneity will not be maintained if it is a very big size. So, there are some standard sizes so, like 100 mm diameter, round single crystalline and for again single crystalline will have 100 mm area is normally now recommend by industry. And in case of multi crystalline, it is something like 100 mm×100 mm or maybe sometimes 125 mm×125mm.

The thickness of this silicon wafer, which industry normally prefer is in the range of 200 to 400 µm. And this PV cells are classified based on different aspects. So, primarily there are three aspects like thickness of active material, then type of junction structure and type of active material used in the fabrications.

So, we will learn slowly, what is active or bulk material and then thin film. So, this bulk material false maybe we will have single crystalline cells or maybe multi crystalline solar cells. And thin film maybe organic solar cells. So, thin films we can bend it, but this bulk material if we have to have more active material then we cannot bend it. So, but thin film can be bended.

And for junctions, we will have PN junctions that may be homogeneous or maybe heterozygous or maybe p-i-n, so p type-intrinsic and n-type semiconductor junction. And, third category is type of active material used that maybe single crystal silicon solar cells or maybe multi crystalline solar cells, et cetera.

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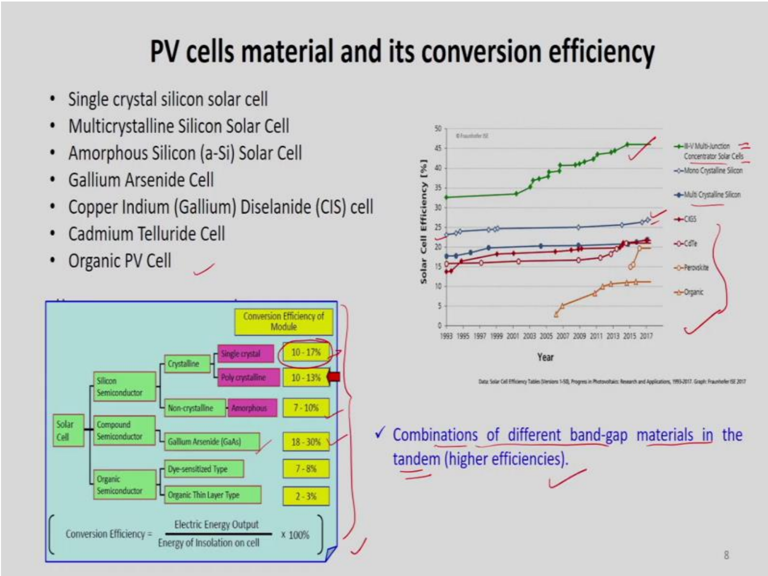

So, let us see how these efficiencies or conversion efficiency varies with different solar cells. So, already we have learned the different kinds of material used for conversion of solar energy to electricity by using different cells, it may be single crystal solar cells, may be multi crystalline solar cells, amorphous solar cells, gallium arsenide, copper indium, diselanide, then cadmium telluride cell, then organic solar cells. So, this chart shows about the conversion efficiencies of the solar cells.

So, in case of single crystal solar cells will have 10% to 17% and of course, this efficiency is increasing which more manufacturing or precise manufacturing techniques. And polycrystalline is 10 to 13, then amorphous is 7 to 10, then gallium arsenide is having very high percentage of conversion, but it is very, very costly; availability of material is an issue. Then dye sensitised is reported to be 7 to 8, then organic thin film is 2 to 3.

So, these are the efficiency list and here this figure shows the solar cell efficiency and how this development is taking place. If we consider this the top most figure or top most line, this is for multi junction concentrator solar cells, having very high efficiency; it is more than 45%. And in case of mono crystalline solar cells, what you can see this is the line. So, it varies from may be 23 to may be 26, 27 that range and in case of multi crystalline solar cells, this variation is may be from 16 to about 22 %.

So, others can be seen here. So, it shows the development how with time and then with new schemes and new methodology, we can increase the solar cell efficiency. So, these multi junction solar cells are nothing but combinations of different band-gap materials in the tandem cell, of course, we will get higher efficiencies in those cases.

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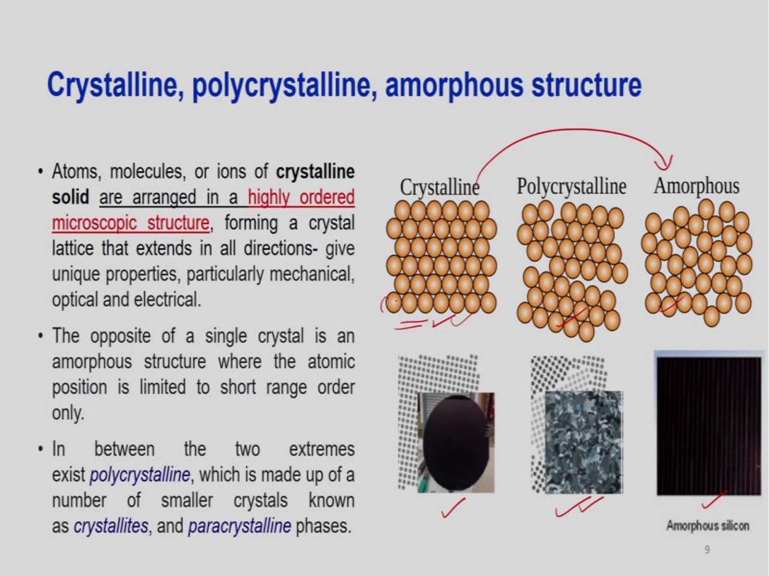

So, now see the structure of crystalline, polycrystalline and amorphous solar cells. So, in case of crystalline structure, this constitutents like atoms, molecules and ions are arranged in a highly ordered microscopic structure. What you can see, these are highly ordered microscopic structure and this forms a crystal. And this gives an unique properties, particularly mechanical, optical and electrical. So, it gives mechanical properties it is very, very strength and then optical properties, no light can enter and then it has got very good electrical properties.

And reverse of this system is something called amorphous systems. So, they are not closely picked and when we talk about polycrystalline, it is in between crystalline and amorphous systems, amorphous atoms or atomic structures.

So, here number of crystals will be there as you can see in this figure, there is a single crystal, there is a multi crystal and there are many crystals, grains are there many grains, and amorphous structure is something like that. So, just to introduce how it looked likes, and we will study how these crystals are formed, so these are atoms, so if we combine these then it will becomes crystals. So, everything will be discussed when we discuss semiconductor physics.

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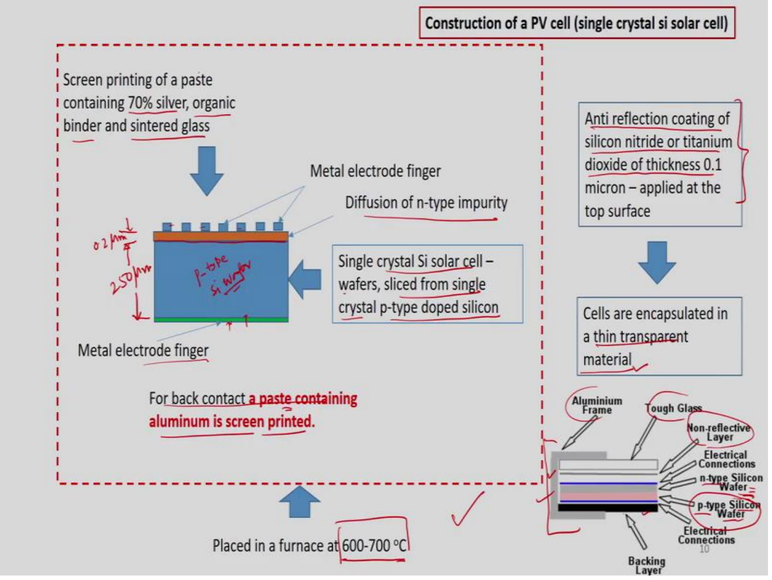

So, now let us learn about construction of a PV cell and of course, it is a single crystal silicon solar cells. So, how this can be done? So, before we touch this now, basic concepts, let us see how, what are different layers exist in the PV cells.

So, we will have back layer, at the backside, you can see some kind of installations is provided and we must have electrical connections because the kind of energy what is generated that has to be collected. And then p type silicon wafers, so this is the main thing first you have to take. So, this p type silicon wafer is nothing but this is the p type semicon, p type silicon wafers. And this is something like about 250 μm, so this upto this here.

Then we have n type silicon wafer, so this is n type silicon wafer here and it is about 0.2 μm. So, this diffusion so we have to make some kind of junction. So, this is made by diffusing n type impurity here. So, this is something called n type silicon wafer and then we have to have some kind of metal grids or metal electrode fingers, so these are metal electrode fingers. So, we need to connect, the kind of energy we can generate here, or electron, there has to be transferred. So, we need some kind of metal connections.

And then we will have non-reflective layer and then toughened glass and then we have frame. So, now we will come back here. So, now come back to this, our main discussion chart. So, we will have p type wafers and this is a single crystal silicon solar cells and it is slice from single crystal p type doped silicon. So, this is having thickness of 250 μm and then in order to make junction, we are diffusing n-type impurity here and then we will have metal grids. So, these are transparent to the solar radiations and then what we have to do?

We have to do some kind of screen printing of paste containing 70% silver organic binder and sintered glasses, which is laid over this metal electrode fingers in the front side. And the back side, again we will have metal electrode fingers and we will have to make a paste containing aluminium. So, this paste is applied here and then we kept this entire system or entire this wafers and then connections in a furnace and maintain a temperature range of 600 to 700 ^{o}C.

So that this metal content in the paste is come in contact with this silicon, what is present here, for transfer of electrons or generation of electricity. Once this is done then, what we will do? We will apply anti reflection coating of the silicon nitride or titanium dioxide of thickness 0.1 μm. So, this is applied. This is anti reflection coating, so that reflection losses are minimised.

And finally this cells once that is prepared, these cells are encapsulated in a thin transparent material, what you have seen here. So, this is a back layer, then we have electrical connections, then p-type silicon wafer, then n-type silicon wafer, then electrical connection, then non-reflecting layer, then toughened glass or something like transparent material. Because solar radiation has to pass through and then strike on the absorber right. And then in order to hold the system, we need a frame; so these frames are made of aluminium. So, this is how a PV cell constitute, so construction is something like that.

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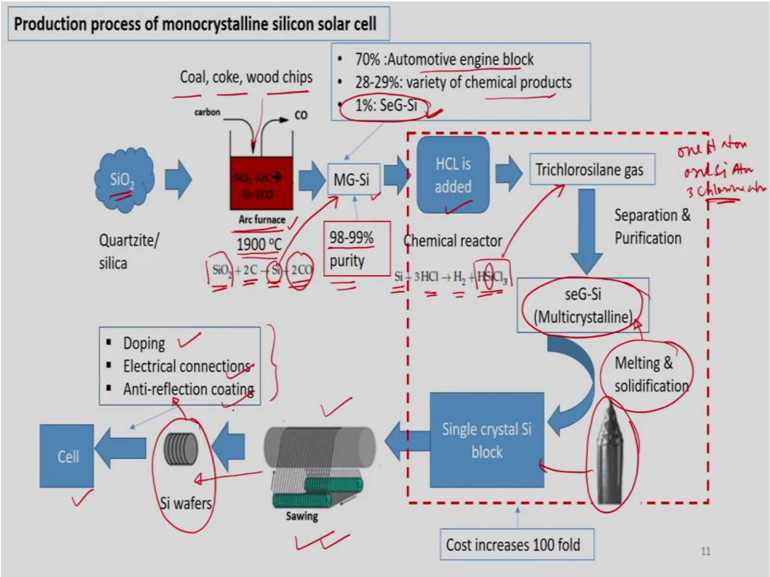

So, let us now learn how this PV cells are manufactured, which is very, very important. Because see what we know, this silicon is the second most available element in the earth, after oxygen. So, the kind of form we will get is a silicon dioxide SiO_2. So, once we have SiO_2 then, what we need to do for production of these cells, first this has to be melted in a furnace, normally this arc furnace is used and at a temperature of 1900 °C.

So, once we maintain this at that temperature, what will happen and also we need to add carbon so what are sources of carbon, sources of carbons are like coal, coke, wood chips. This can be added here and this silicon dioxide in the raw form will react with carbon, will form silicon plus carbon monoxide. So, this CO will be generated and it will goes off and this silicon the kind of silicon what we will get on doing this is a metallurgical grade silicon. So, it contains about 1 to 2 % impurity, its purity level is 98% to 99%.

So, this metallurgical grade silicone cannot be used for making solar cells. So, we need to do something to upgrade the quality of this metallurgical grade solar cell. But there are multiple applications of this metallurgical grade solar cell, like in automotive engine blocks, in automotive industries, 70% of these kind of metallurgical grade solar cells are used in automotive industries. And about 20% to 29% is used in a variety of chemical products making and only 1% is used for making semiconductor grade silicon. So, how to convert this so, our concern is now 1% conversion for making cells.

So, what we need to do, once we have this metallurgical grade solar cells or this metallurgical grade silicon; so this has to be processed by using hydrochloric acid. So, once we process it, then what will happen? Si + 3 HCl → H_2 + $HSiCl_3$, which is nothing but trichlorosilane gas, this is nothing but trichlorosilane gas. So, here what happens we have one H atom one H atom, then one Si atom, then 3 Cl atom Cl atom.

So, you need Si, not H_2 and Cl_2. So, we have to do some kind of distillation. So, once we do distillation or purifications, because other impurities which is present along with this trichlorosilane gas has to be removed by using distillations. Because all the elements are having different boiling points.

So, we can remove it very easily, once we analyse critically. And once we are done with that, then, what we will get is a semiconductor grade silicon, which is in multicrystalline form. So, this is in multicrystalline form, but we need single crystal silicon blocks. So, in order to convert this multicrystalline to silicon, single crystal silicon blocks, then again we need to melt it and we have to solidify on a rod containing high purity silicones. So, it will look something like this, this is called ingot. So, this kind of blocks we can make by using this process.

And finally, once we make this kind of block, then we have to saw it, so wear saw, so this sawing machine, the role of sawing is very, very important. Because most of the cases, this losses are very, very high if we use ordinary saw. So, this is a very precise saw, now industrial scale this kind of saws are used. So, this has to be sliced and these slices are nothing, but wafers. So, once these wafers are ready, then what we can do? We can processing like doping, electrical connections then anti reflection coating. Because this has to pass through some phosphorus vapour so that phosphorus can be deposited and it will become p-type silicon cells or wafers.

And then, once we are done with this doping, electrical connections and anti reflection coating, what we will get that a cell, which is ready for generation of power. So, this is very, very important as far as production process of monocrystalline silicon cells are concerned.

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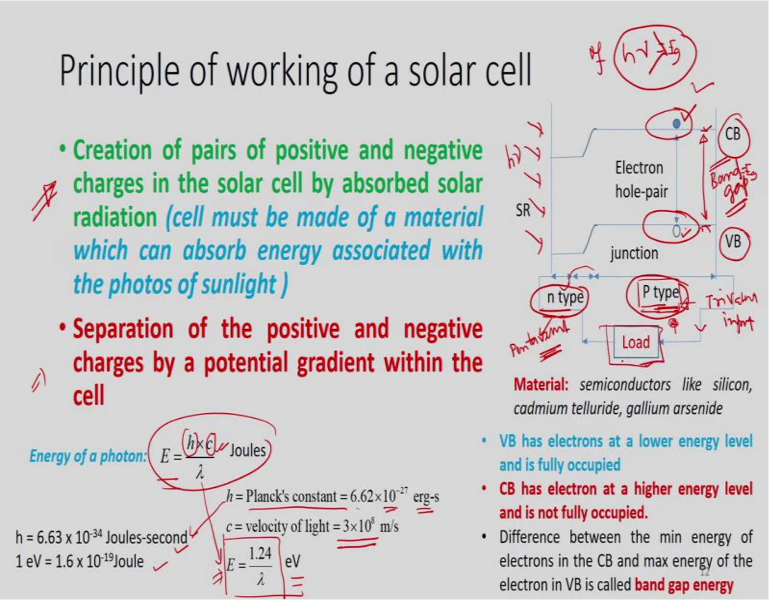

So, now let us now learn the principle of working of a solar cell. How does a solar cell works? So far, we know the construction and then know how the solar cells are manufactured. Now, we would like to know how the solar cell works. What is the working principle?

There are two steps working principle, first step is creation of pairs of positive and negative charges in the solar cells by absorbed solar radiation. So, the material what we consider, that has to be capable enough to absorb the energy associated with the photons in the sunlight. And once that is created, then we have to separate it by using a potential voltage, which is built in it.

So, we will have two principles or two working principles, that is creation of pairs of positive and negative charges, then separation of positive and negative charges by potential gradient within the cell. So, it is certain that the material what we use, that material has the capability to absorb the energy associated with the photons carried by sunlight.

Now, let us see this figure here, we will have two band this is VB means valence band and CB means conduction band. So, electron will occupy any of the bands. So, this valence band has electrons at lower energy level and it is normally fully occupied. And in conduction band has electrons at a higher energy level and it is not fully occupied.

So, this difference between this minimum energy of this conduction band and maximum energy of this energy of the electron of this valance band is known as band-gap. So, role of the band-gap is very, very important. So, if this energy of the photon is $h\upsilon$ and if we represent this band-gap as E_g. So, if $h\upsilon = E_g$, then it will be difficult to transfer electron from this valance band to the conduction band. It has to be something like $H_g \geq E_g$, then only electron can be shifted from valance band to the conduction band.

So, this $h\upsilon$ is something like hc/λ. So, h is the Planck's constant and c is the velocity of light, which is something like the value of the velocity of light is 3×10^8 m/s and Planck's constant is 6.62×10^{-27} erg-s. We can also represent in Joule, so 6.63×10^{-34} J-s.

And also one eV = 1.6×10^{-19} J. So, on substitution of these values here, then what we will get? e will be something like $1.24/\lambda$ and it will be in eV. So, if we know this band-gap energy, then we can calculate the optimum wavelength to lift or excite one electron from the valence band to the conduction band.

So, in the first step, we can create positive and negative charges by applying solar energy; and of course condition is h nu greater than E_g. Now, once it is done then, these electrons in the conduction band and holes in the valence band are mobile. So, they can made to flow if we can connect one external load. So, already we know, this p-type semiconductor or if we consider silicon material and this p-type semiconductors adopt with trivalent impurity trivalent impurity and this n-type adopt to it pentavalent impurity pentavalent impurity. So, this will have extra electron and this p-type has extra holes.

Since, in the second case we need to separate positive and negative charges and we have to create some kind of built in potential. So, how this can be carried out? So, we will make it by doing sandwiching of n-type and p-type doped silicon cells. So, once we make sandwich, then what will happen? Then electron, which is the majority carrier for n-type will diffuse to the holes and recombine; and again holes which is the majority carrier for p-type will recombine with n-type. That creates built in potential, and this built in potential again create some kind of electric field. So, that is enough to circulate or generate electricity once we have external load.

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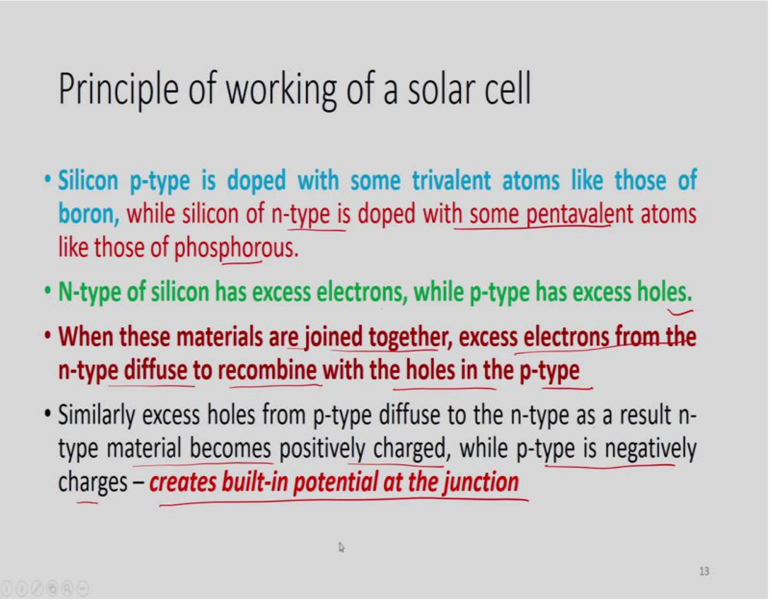

So, what we can say this silicon p-type is doped with some trivalent atom like boron, and while n-type is doped with some pentavalent atoms like phosphorous. So, this n-type silicon has excess electrons and p-type has excess holes. So, when these materials are joined together, excess electrons from the n-type diffuse to recombine with the holes in the p-type.

Similarly, this excess holes from the p-type diffuse to n-type. As a result, n-type material becomes positively charged, while p-type is negatively charged. And that creates a built in potential at the junction, and consequently electric field is capable enough to transfer charges from the negatively charged p-type to the n-type, and then electricity can be generated. This is how a PV cell works.

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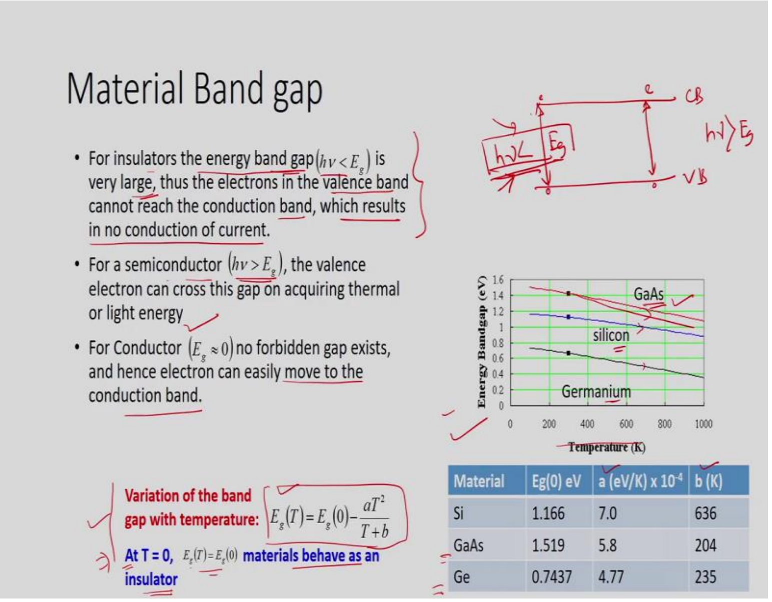

So, now, let us learn something more about material band-gap. As I said, for insulators that energy band-gap is very, very high. So, we have conduction band and we have valence band. So, if we talk about this *hυ* and if we add this E_g, and this may be hole, this may be electron; so no excitation of electron will be here, but if $h\upsilon \geq E_g$, then what will happen, there is a creation of pairs of holes.

So, for insulators that energy band-gap, the h nu is something like that, is very very large, then the electrons in the valence band cannot reach the conduction band, which results in no conduction of current. So, for insulators this $h\upsilon \leq E_g$. For semiconductors, because this conductivity of semiconductor is in between insulator and conductor. So, for semiconductors, *hυ* has to be greater than band-gap energy. The valence electron can cross the gap on acquiring thermal or light energy.

And for conductor, there is no forbidden, no gap exist, hence the electrons can easily move to the conduction band. So, this slide shows the variation of band energy band-gap with respect to temperature. You can see for three different material helium arsenide, silicon and germanium. See how this is decreasing with temperature. And this variation of band-gap with temperature can be predicted by using this relationship. And what is a and b? So, these are constant, these values are given here for silicon, gallium arsenide and then germanium.

So, we can use those values for calculation of E_g at certain temperature. So, at T = 0, at absolute 0 temperature, E_T is E_g. The material behaves as an insulator. So, we should keep in mind that in order to excite electron from the valence band to the conduction band, the temperature has to be more than absolute 0.

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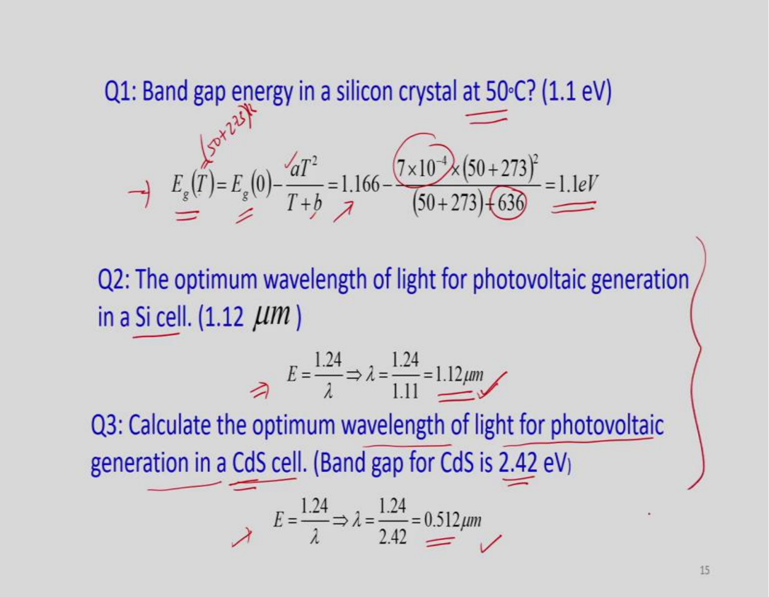

Now, let us do some kind of analyses. Say, for example, if I am interested to know the band-gap energy in a silicon crystal at 50 °C. So, we know the relationship and we know the value constants a and b, then straightaway we can use this relationship. For E_g at certain temperature, this temperature is 50 °C. So, (50+273) K, at this K. So, our calculation will be something like this. So, we know this value E_g (0), what is the value of band-gap and then we know the value of a and b here. And if we substitute this T value, so what we will get is 1.1 eV.

And in second question, maybe the optimum wavelength of light for photovoltaic generation in a silicon cell. So, what will be the optimum wavelength of light if we use silicon cells? So, we can use this relation. Already we know this relation, E = 1.24/λ, which will be the eV and λ is in µm. So, once we know this E value, then we can substitute here and we can get the optimum wavelength of light for the photovoltaic generation.

And also maybe now third question is something like that. Calculate the optimum wavelength of light for photovoltaic generation in a CdS? And band-gap is given to us 2.42 mV. Then under that condition then we can calculate what is E. And it will be 0.512 µm. You see the difference, the optimum wavelength of light for photovoltaic generation in CdS cell is 0.512, but here it is 1.12 µm. See the variations. For solar silicon cells, will have a value of λ = 1.12, which is optimum wavelength for photovoltaic generation. But here, it is 0.512 for photovoltaic generation; that is how we can see. So, this kind of analogies are required sometimes to decide at what condition your system will work perfectly.

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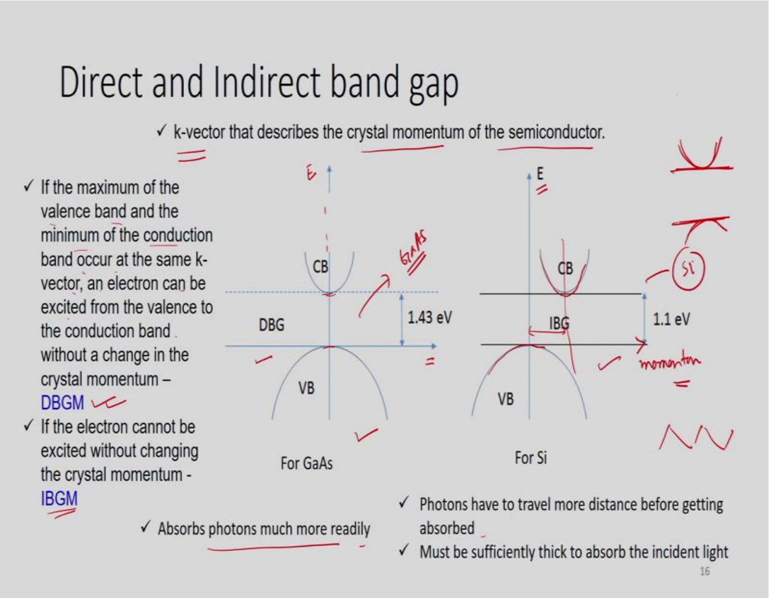

So, there are different classes of band-gaps, maybe direct and indirect band-gaps. So, these are important for improvement of efficiency of conversion. So, here in case of direct band-gap, what happens?

So, this figure shows the variation of E and then momentum of the electron. So, this is the E and energy and then this is your momentum momentum. So, this k vector, there is a term called k vector that describes the crystal momentum of the semiconductor, like a wavy. So, even though we have considered conduction band and valence bands are flat, but this is not so. This is something like that, this is something like that, there is a variations and this is not uniform always. It will like a some kind of wave form.

So, if the maximum of the valence band and the minimum of the conduction band occurs in the same k vector, an electron can excite, can be excited from the valence to the conduction band without a change in the crystal momentum. So, this is known as direct band-gap material.

And if the electron cannot be excited without changing the crystal momentum is called indirect band-gap material. In case of direct band-gap material, as you can see this is peak of this valence band and then bottom of the conduction band are in the same line.

So, what happens, is photon absorbs much more readily. Here what happens in case of indirect band-gap material, so peak of this valence band and this bottom of the conduction band is far away. So, in order to absorb more, then we need to apply many more technologies like some wavy configuration, so that we can get more solar radiations. So, photons have to travel more distance before getting absorbed in case of indirect band-gap material. And that is why, this must be sufficiently thick to absorb the incident light.

So, from this analysis what we can say, in case of direct band-gap material, this thickness of the active material required will be much lower compared to the thickness of the active material required for indirect band-gap material.

So, this is something like silicon will have indirect band-gap material or maybe some maybe gallium arsenide, gallium arsenide is an example for direct band-gap material. So, this is important and also you must know always these are not flap, this will be something like that and this is not uniform as well, always will not get this kind of configuration.

So in summary, what we can say this kind of configurations like direct band-gap materials is photon absorbed most, much more readily and in case of indirect band-gap material, so photons, the distance travel by the photon is very very high. So, we need to do something to reduce it. That is why, sometimes other configurations are applied to capture more photons of sunlight.

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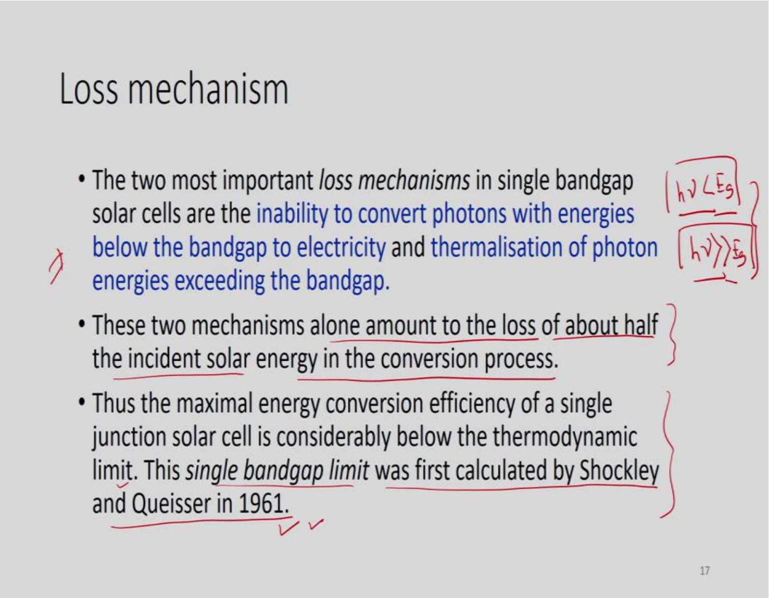

So, let us now discuss something on loss mechanism. So, as far as last mechanisms are concerned, we will have two most important loss mechanisms in single band-gap solar cells. Number one, is inability to convert photons with energies below the band-gap of electricity. And the second one is thermalization of photon energies exceeding the band-gap.

As you can understand, so if this $h\upsilon \leq E_g$, that is band-gap energy, we cannot excite electrons from balance band to the conduction band. And if this $h\upsilon >> E_g$, then what will happen; energy will escape and then heating effect will be there. So, these are the two primary reasons why we get lesser conversion efficiencies in case of single band-gap material. That is why you can see in one of the slides, we have discussed why multi junction solar cells are important.

So, slowly you will learn the importance of those aspects. And these two mechanisms alone account to the loss of about half of incident solar energy in the conversion process. So, this is the primary losses taking place because of these two phenomena.

Thus, this maximal energy conversion efficiency of a single junction solar cell is considerably below the thermodynamic limit. So, this single band-gap limit was first calculated by Solski and Queisser in 1961. That is how it is known as Solski and Queisser investigations, or cellular limitations or the losses.

So, these are the primary losses. So, it involves lot of analysis. So, we can sometimes show, how this can be calculated? This thermodynamic limit and why this is so; and we can mathematically prove it as well.

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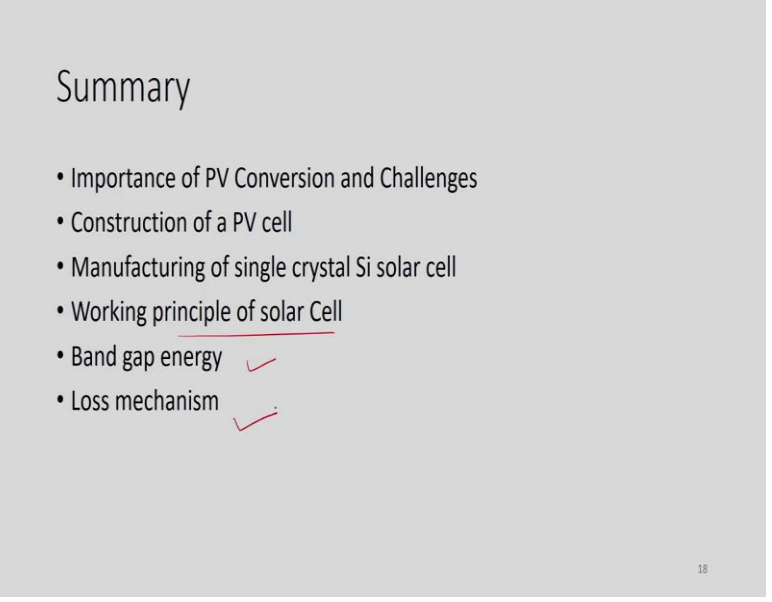

So, let us summarize what we have discussed today, we have discussed the importance of PV conversion and challenges and distinction between cells, modules and arrays and what are applications of cells, modules and arrays. And also we have learned the construction of a PV cells. So, we will have wafers maybe p-type doped, then we have to make junction. For making junction, we have to apply or diffuse n-type impurities and then we have to give metallic connections and then we have to apply some kind of paste, metallic paste on the top and the back side. And then we have to keep that entire system at a temperature of 600 to 700 in a furnace in order to have metal contact between the silicon and metal present in the paste.

And then finally, we need to apply anti reflection coating, then we have to keep in an encapsulation, then the cell is ready for use. And also we have studied the manufacturing of silicon solar cells. So, how this silicon dioxide is converted to metallurgical grade.

So, we have also discussed the applications of metallurgical grade silicon solar cells and then the process used for converting these metallurgical grade solar cell to the semiconductor grade solar cells. So, we have seen the making of ingots and then slicing by using very precise saws. And then finally, this wafers are generated, then wafers are passed through some furnace where phosphorous is deposited and then p-type semiconductor is produced.

And then finally, this all the connections and n-types are also applied and the impurities are also applied. And then electric connections are provided and then all other things required for making PV cells are generated. Finally, what we get, that is a PV cells which is ready for generation of power.

And also we have studied different band-gap energies and before that, we have studied working principle of solar cells. So, how this solar cell works? Like first generation of electron hole pair, then separation of those electrons from conduction band, from valence band to the conduction band. And then, we have studied band-gap energy, then we have also studied the loss mechanism, what are different losses associated with this system.

So, thank you very much for watching these videos. So, the next lecture it will be on semiconductor physics.