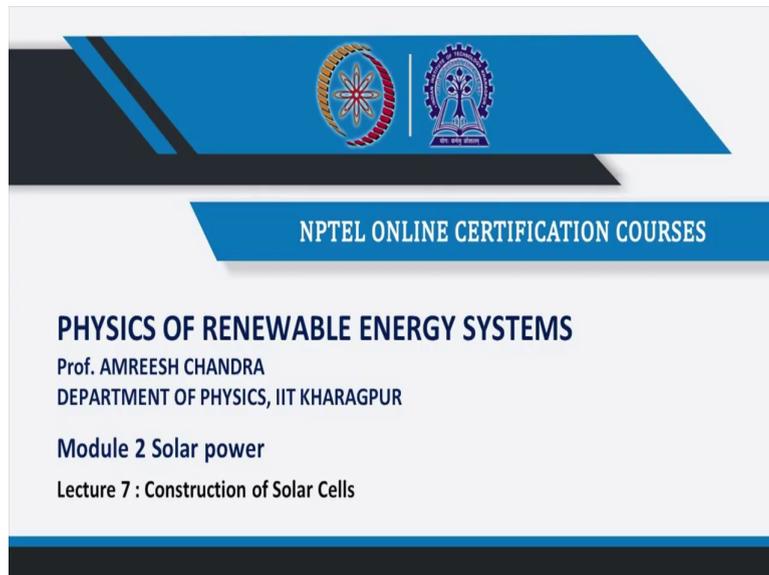


Physics of Renewable Energy Systems
Professor Amreesh Chandra
Department of Physics
Indian Institute of Technology Kharagpur
Lecture 07
Construction of Solar Cells

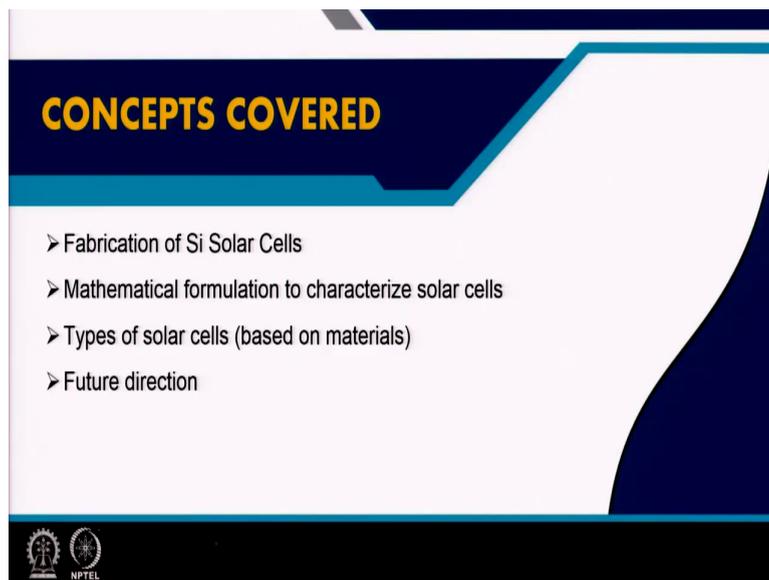
Hello, welcome to the course on Physics of Renewable Energy Systems. Till previous lecture, we have been talking to you about the basics of solar cells and how do we use solar radiations for our use and to fabricate a very useful device that is called a solar cell.

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And in today's lecture, let us start to understand slightly more in detail the construction of solar cells, how can you fabricate solar cells, how do you use various processes to make different types of solar cells and then you can take those solar cells to real world applications.

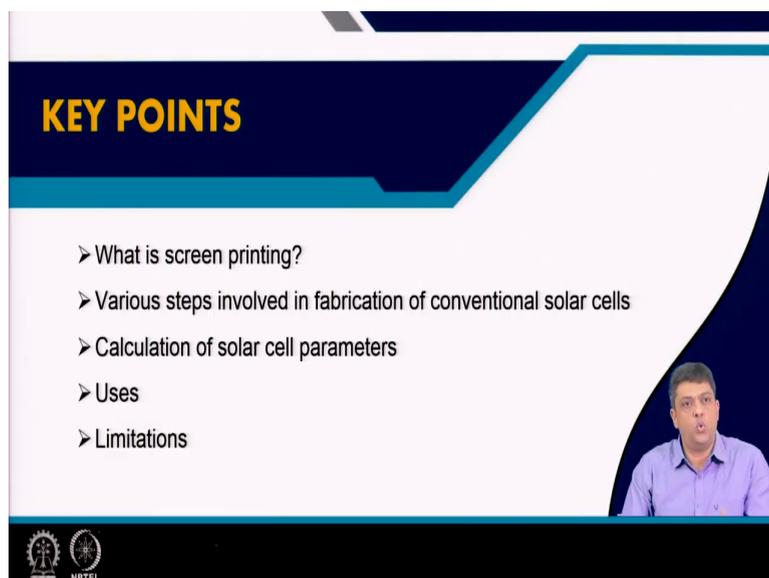
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So, in today's class, I would like to give you some details about the fabrication procedure to obtain silicon solar cells. We will also start with certain mathematical formulations to characterize these solar cells. And we will see that, it is important to understand the different kinds of materials those are used to make these solar cells because based on them, the classification of solar cells are made.

And before I end today's lecture, will also start giving you some future prospects about this field, if you want to carry out research in this field, or you want to understand more about the next generation solar cells, then what is the future direction this field is moving towards.

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So, the key points which would be the take home message would be you will understand what is screen printing and how that is used to fabricate solar cells. And if I start screen printing of solar cells, then what are the various steps involved in fabricating a conventional solar cell using this screen-printing process. We will also start with some calculation of solar cell parameters. And you would also be able to understand the uses of the solar cells and also the associated limitations with different kinds of solar cells.

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In the previous lectures, we have seen...

p- and n-type semiconductors

Schematic of a silicon crystal lattice doped with impurities to produce n-type and p-type semiconductor material.

	P-type (positive)	N-type (negative)
Dopant	Group III (E.g. Boron)	Group V (e.g. Phosphorous)
Bonds	Missing Electrons (Holes)	Excess Electrons
Majority Carriers	Holes ✓	Electrons ✓
Minority Carriers	Electrons ✓	Holes ✓

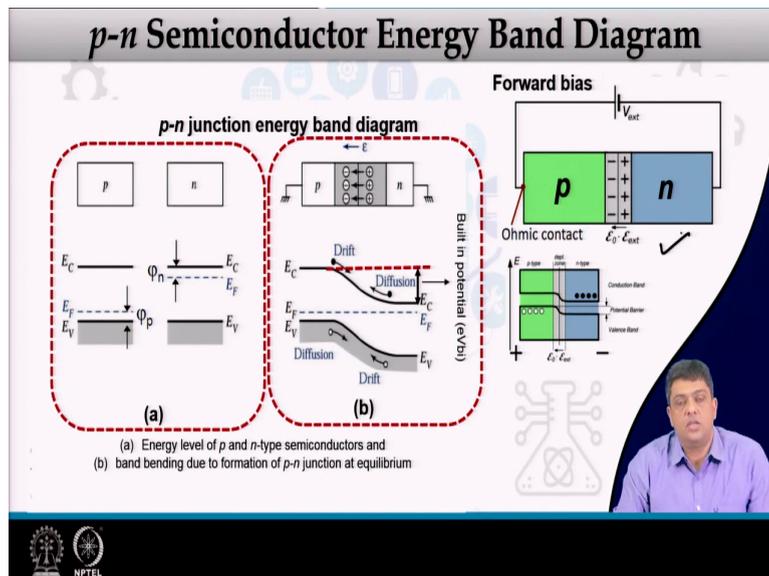
In the previous lectures, what have we seen? We have talked to you about the classification of solid materials into metals, insulators and semiconductors and because we would be using semiconductors to fabricate solar based devices, we started with our focus on semiconductors. And we have given you the details about the semiconductors. What are semiconductors? What do we mean by intrinsic and extrinsic semiconductors?

And what are the majority carriers if I talk to you about p-type semiconductor or an n-type semiconductor, please note that majority carriers and minority carriers are two concepts which go hand in hand in p-type and n-type semiconductors. So, if I am talking about an n-type semiconductor, it does not mean that there are no contribution coming in from the conduction of holes.

But the contribution is less and the number of holes which are contributing in the overall conduction process are much less than the majority carriers which in this case are the electrons in n-type semiconductors. So, you can take two types of semiconductors and when

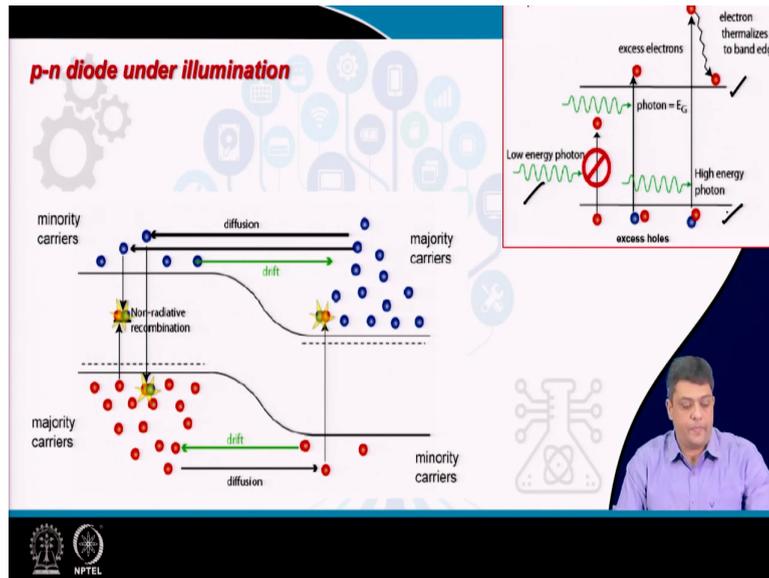
you make the junction using different kinds of processes, which we discussed in the previous class, you will find that you will obtain a junction and this kind of a device is called a p-n junction diode or a p-n junction device. This is what we discussed in the previous lecture. Let us build further knowledge, so as to make a silicon based solar cell.

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Now, we know that in a p-n junction what is happening? You have two regions. You have the p-type and the n-type. And then there are two concepts which take place, one is the drift current and the other is the diffusion current. And one you will see that in terms of when you bias this junction. You will have two types of biasing. One is forward bias and the second is the reverse bias.

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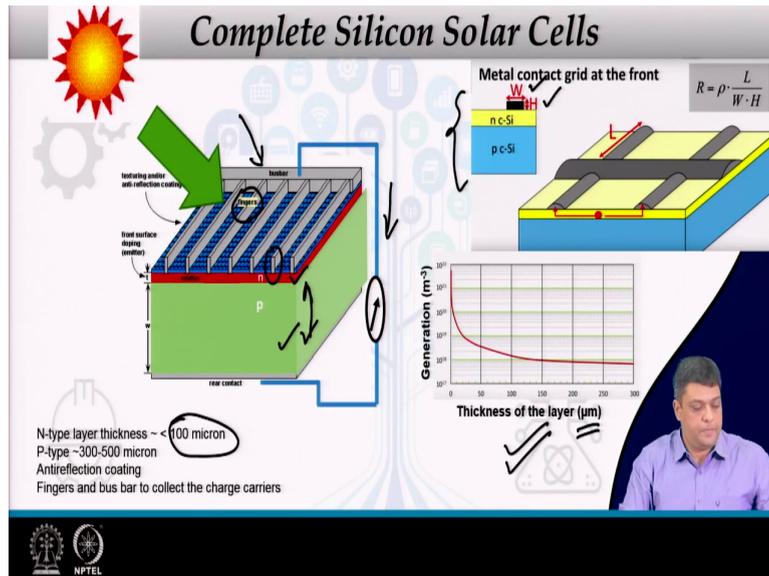


Now, what did we do in the previous class, we had a p-n junction and what we will be focusing on that we would focus the light in such a way that it illuminates the depletion layer and the whole system was in the reverse bias, so that the depletion layer was having a width which is much more than what we get in the forward bias.

And if you have photons, which are of low energy, no transfer or excitation of electrons from lower energy level to a higher energy level takes place and the energy level which I am talking about is the valence band and the conduction band not the two consecutive bands or levels in a valence band or conduction band.

We are talking about a transformation from valence band to conduction band. So, once that happens, you have electrons in n-type, which can flow from the outer circuit and then they go through a lot and then combined with holes in the p-type. So, as to ensure the condition of charge neutrality of the overall system.

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And this is a typical design of a complete silicon solar cell, how does it look like you will see that you have a p-type substrate. On top of it, you have grown an n-layer and on top of it, you have the texturing or anti reflecting coatings and you have the fingers. So, these are the conducting materials which are used to collect the electrons which are taking part in the conduction and will flow through the external load.

So, this is a typical solar cell and the metal contact grid at the front of these solar cell you can take a cross section and the cross section looks something like the finger which is drawn in the middle of the two extremes. So, if you take the finger, if you take a particular finger, then that finger has a width and a height and the resistance which you then will get will be equal to $\rho \frac{L}{W \cdot H}$.

And the number of charge carriers which are generated or can be collected strongly depends on the thickness of the layers and that is clearly visible from a plot which is showing the generation of carriers as a function of layer in micrometres. And the typical dimensions what you get in a solar cell, the n-type layer thickness is approximately 100 micrometres. p-type is 300 to 500 micrometres.

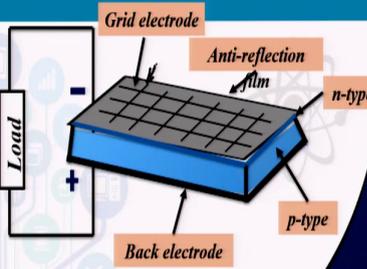
And on top of it depending upon the requirement, you choose the thickness of the anti-reflective coatings and the height and the width of the fingers. What is the requirement of this busbar will become clear to you, after we have finished our discussion on the fabrication of solar cells, and then I will show you this slide once again and you will be able to

understand why this busbar is used, which I am not explaining at this moment. So, this is a typical silicon solar cell which is available to you in the market. Let us see how to fabricate it.

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Steps involved during fabrications

- ❖ Constructed on a thin single crystal of silicon.
- ❖ Form a p-n junction.
- ❖ The thickness ($\sim 1 \mu\text{m}$) of the n-type region is much less than the thickness ($\sim 300 \mu\text{m}$) of the p-type region.
- ❖ The n-type is more heavily doped.
- ❖ Typically a cell may be $\sim 10 \text{ cm} \times 10 \text{ cm}$.
- ❖ A grid of wires and the semiconductor surface to provide electrical contact to the cell.
- ❖ Light collection can be enhanced by texturing the front surface of the solar cell by a chemical etching process.



The diagram illustrates a silicon solar cell with the following components labeled: Grid electrode, Anti-reflection film, n-type, p-type, and Back electrode. A circuit diagram shows the cell connected to a Load, with the n-type region being the negative terminal (-) and the p-type region being the positive terminal (+).



A small inset video shows a man in a blue shirt speaking.

So, the steps involved during the fabrication of this solar cell are going to be discussed in next 3 to 4 slides. So, let us start and to start you should realize that the construction is carried out on a thin single crystal of silicon. So, you take a thin single crystalline silicon, then you form a p-n junction. I hope you can list 3 to 4 methods by which you can make a p-type layer in an n-type substrate or vice versa.

I hope you remember about the process of diffusion using lithography or you can discuss about ion implantation, what are the advantages of ion implantation over lithography, which of the techniques work at lower temperatures. If you do not remember, please refer to the lecture which was given earlier and then you will be able to understand the way to form a p-n junction and depending upon the requirement, you will choose which method to apply.

Then, once I have formed the p-n junction, I ensure that the thickness is approximately 1 micrometre for n-type region and for a p-type region because I am growing an n-type layer on top of a p-type substrate in this example, which I have chosen. The thickness of the p-type region is approximately 300 micrometres, the n-type is more heavily doped. So, you have the concentration of majority carriers is higher.

And typically, right from beginning or up till standardization you can talk about a cell which can be in an area of 10 cross 10 centimetre length and breadth and in terms of complete area

that is approximately 100 centimetre square. And then you need a grid of wires, and the semiconductors surface to provide the electrical contact to the cell. So, what are you doing?

You have a grid, suppose, I take if you see the finger and if this is the substrate, I am pasting the finger on top of this substrate. So, these are going to act as the grid of wires which will be used to collect the charges. And then because you have made a grid use make sure that certain light passed through these current collectors. If I would have closed the network, then what would have happened, then no light would have passed from the top of this electron.

But now that I opened this grid the light can pass through and it can fall on the substrate. That is what I mean that light collection can be enhanced by ensuring certain level of distance between the fingers and by texturing the front surface of the solar cell by chemical etching process.

So, what you do, you can change the texturing of the surface face, so that there are reflecting surfaces, which makes sure that the light which falls have multiple reflections and ensure higher order of absorption at the surface. So, you can change the texturing of the substrate layer itself.

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Before using the substrate, it is refined using the following steps"

- ❖ Silica (SiO_2) is reduced (oxygen removed) through a reaction with carbon in the form of coal, charcoal, and heating to 1500-2000 °C in an electrode arc furnace.

$$\text{SiO}_2 + \text{C} \rightarrow \text{Si} + \text{CO}_2$$

Result: 98% pure Silicon with slight amount of Fe, Al, and B.

- ❖ What next? Further purification is required:

$$\text{Si} + 3\text{HCl} \rightarrow \text{SiHCl}_3 + \text{H}_2$$

Result: Formation of halides viz., FeCl_3 , AlCl_3 , BCl_3 .

- ❖ SiHCl_3 has a low boiling point of 31.8 °C.
- ❖ Distillation process can be used to separate it from impurities.
- ❖ Finally, the pure SiHCl_3 is reacted with hydrogen at 1100 °C for 200-300 h to produce a very pure form of silicon.

$$\text{SiHCl}_3 + \text{H}_2 \rightarrow \text{Si} + 3\text{HCl}$$


But you may have seen that silicon cells are still not very cheap, there are a lot of the cost which is significantly high, if you want to use it on a regular basis and for large number of applications. The reason is that there are many steps which have to be performed before a cell is ready for delivery to an end user. To start, let us discuss just about this substrate.

So, suppose, I take a silicon which was exposed to air and then whenever there is oxygen flowing on top of silicon what happens, you form a layer of silicon dioxide. But this is an insulating layer. So, how do I use this substrate? So, I have to remove this top insulating silicon dioxide layer, so as to get access to the semi conducting layer, which is at the bottom of silicon dioxide layer.

So, silicon dioxide is reduced through a reaction with carbon which can be in a form of coal or charcoal and that is heated to very high temperatures, we are talking about temperatures in the range of 1500 to 2000 degrees and they are not going to be heated in normal furnaces, they are heated in arc furnaces. So, what reaction takes place? Silicon dioxide reacts with carbon and gives you silicon and carbon dioxide.

The result is that by this process, you obtain 98 percent pure silicon. But still, you still have impurities which include iron, aluminium, boron. So, these kinds of impurities are still present in the semiconductor vapour are the substrate on which you want to fabricate your cell or the you want to use that substrate to fabricate a junction-based diode. So, what next, what should we do?

So, the next step involves the treatment of this, so called of 98 percent silicon substrate with an acid. In this case, let us say HCl and you get halides of iron, aluminium, boron forming along with silica. Now, what happens? The advantage comes with the fact that SiHCl_3 has low boiling point of 38 point 8 degrees. What is the boiling point of water? I guess you remember it is 100 degrees.

Now, this is going to boil just at 38 point 8 degrees. So, immediately for purification of water, what process do you use? You use the process of distillation that we have been learning from our school days. So, can we use a similar distillation process to separate the impurities in the vapour which we are using and that is exactly what is done. So, distillation process is then used to separate the impurities from SiHCl_3 .

And finally, this pure SiHCl_3 is reacted with hydrogen at around 1100 degrees and look at the time we are talking about, approximately 200 to 300 hours to produce pure silicon. So, if I just talk to you and ask you that please draw a rough estimate on the timescale we are talking to obtain silicon, which is pure and can be used to make a p-n junction diode.

You will find it involves a significant amount of time and it also involves trained manpower, people who are trained and they have a lot of knowledge about these processes and train manpower is also very expensive. And if you add the total cost, you will find the cost of obtaining pure silicon substrate becomes quite significantly high. And therefore, the device which we fabricate using this silicon will also be quite high.

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Screen printing of Si solar cell

- ❖ It's a relatively simple process where a mesh is used to transfer ink onto a substrate.
- ❖ The mesh structures prevents transfer of ink into the areas made impermeable by the blocking stencil.
- ❖ A blade is moved across the screen to fill the open mesh apertures with ink.
- ❖ A reverse stroke then causes the screen to
 - touch the substrate momentarily along a line of contact.
 - Ink once again wets the substrate.
 - Extra ink is pulled out of the mesh apertures

The slide features a background with faint icons of a gear, a lightbulb, a laptop, and a chemical flask. A video inset in the bottom right corner shows a man in a blue shirt speaking. The NPTEL logo is visible in the bottom left corner.

So, now, I have got a pure substrate. Then we use a screen-printing process to obtain the silicon-based p-n junction diode which can be used in solar cell fabrication. So, if you have seen in recent years in festivals like Diwali, you get this mesh using which you make rangolis. So, you have this mesh on top of it, you have the flour or any kind of powder which you then sprinkle or spread and then using another pressure applying or a substrate which can be used to apply pressure on that mesh, you pass through this powder through the openings in the mesh and the structure is printed on the floor and then you lift the mesh and take it away.

What happens? The open areas in the mesh which are open allow the powders to go through and the opaque area or the solid areas do not allow the powders to go through. This is a crude way to start our discussion on screen printing. Just an elementary idea we are giving you to think along that direction. Scientifically, we will go one by one and understand each and every step.

You will find that screen printing method to obtain silicon solar cell is a relatively simple process where a mesh is used. A mesh is used to transfer ink on to a substrate. So, you have a mesh, you have a mesh which is placed on the substrate and using this structure which is on the mesh you transfer the ink on the substrate. This mesh structure prevents the transfer of ink into the areas made impermeable by the blocking stencil.

Let me take the example of this hand once again. So, if this is a substrate, and I put another hand and then you want to pass an ink through the top layer, what do we expect? There is no ink which will pass through the top hand. Why, because it is impermeable. But if I open the structure, and then I want to flow some of the fluids which I am going to use to fabricate let us say a structure on these substrates, then with the areas where there are openings, you will have the fluid or the ink in this case to flow through.

So, this is what I mean that the mesh structure prevents the transfer of the ink in those area which are impermeable. Now once I have the mesh, I use a blade and on top of this substrate I move it with slight pressure. What happens with because of that pressure, the ink is compressed in the mesh and then it is pressed downwards onto the substrate and it gets imprinted on the substrate.

So, this was in the forward movement. And then you during the reverse stroke also some of the interesting things happen, what are those, because of this during the reverse stroke, this

substrate momentarily along a line of contact touch the substrate. So, while you are moving back, you also make these lines to press further on to the substrate. So, you can make these inks to separate from each other.

So, you ensure that there is no contacts which are being made. So, it is like during the backflow this line, the substrates with because of the mesh, impermeable lines they separate the inks. Ink once again wets the substrate. So, if there are some ink which had not gone into the substrate, it again goes into the, through the area which was allowing its flow downwards and then gets imprinted.

And finally, if you had some extra ink on the top of the mesh, then they are removed. And once that those are removed, you can pick up the mesh remove it and what you will get is a printed structure which you require. So, this is the typical process which is used to fabricate a silicon based solar cell using screen printing.

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❖ The reactions take place inside large vacuum chambers.

❖ Silicon used for solar cell can be single crystalline, multi-crystalline, polycrystalline, or amorphous.

So, as I told you, earlier, the reactions take place inside large vacuum chambers. Why because these vacuum chambers ensure that the reactions are taking place in absence of air, because if there are gases present, then one amongst them that is oxygen may react with silicon and form an insulating layer of silicon dioxide on top of the silicon substrate. There are various forms of silicon which can be used to fabricate the solar cells, which we have just discussed.

You can take single crystalline silicon, you can take multi crystalline silicon, you can take polycrystalline silicon or more recently, people are also working extensively on the development of amorphous silicon based solar cells. Again, the whole idea lies in improving the efficiencies of these solar cells.

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Steps for screen printing of Si solar cell

Junction formation by doping:

- ❖ Heating the wafer in a furnace (800-1000 °C).
- ❖ The phosphorous atmosphere causes a small amount of phosphorous to be incorporated in the outer layers of silicon.

Screen printing the rear contact:

- ❖ Rear of cell means that the wafer is upside down.
- ❖ The screen printed rear contact is dried in an oven to drive off the organic solvents and binders.

p-type Bulk

Phosphorous atoms producing n-type layer

The slide features a diagram of a rectangular silicon wafer with a central blue box labeled 'p-type Bulk' and a red hatched border representing the 'n-type layer' formed by phosphorus doping. An arrow points from the text 'Phosphorous atoms producing n-type layer' to this border. The slide also includes a small inset video of a presenter in the bottom right corner and logos for IIT Bombay and NPTEL at the bottom left.

So, once again, let us quickly see the real process I have explained to you the screen printing and now let us see how do we, now do the same thing on top of a p-type substrate. So, junction formation is performed at temperatures between 800 to 1000 degree C, you take a p-type substrate and by phosphorus doping, you grow an n-type layer.

Now, when I have to if you remember the silicon based solar cell which I was talking, you had two contacts, current collectors on the top and an electrode at the bottom also. So, during the screen-printing process of the solar cells, the rear is printed first before the top surface. So, what does it mean that? In the first step you print the rear of the solar cell and what do you print?

You print a metallic contact on the surface which is going to be on the rear side that is the bottom side of the solar cells. The screen-printed rear contact is dried in an oven which ensures the removal of the volatile components and the binders. So, that now you have a metallic surface on the rear side.

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Steps for screen printing of Si solar cell

Firing the rear contact:

- ❖ The cell is placed in a second furnace at a much higher temperature to fire the metal contact onto contact with the silicon.
- ❖ The firing process destroys the rear n-layer so that the metal makes contact with the p-type bulk.
- ❖ The cell is flipped over for printing on the front.

Printing the front contact:

- ❖ The front contact is printed in a similar manner to the rear contact.
- ❖ A pattern of the lined is used to prevent shading of the cell.
- ❖ A furnace heats the cell to a high temperature to fire the metal paste into the silicon.
- ❖ The finished cell is ready for encapsulation onto a module.



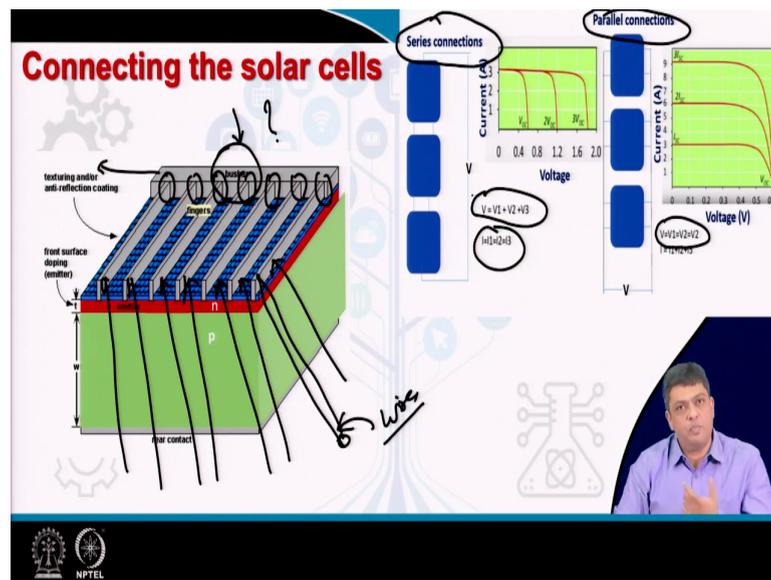
The slide features a background with a blue and white color scheme, including a stylized atomic symbol and a circuit board pattern. At the bottom left, there are logos for IIT Bombay and NPTEL.

Then you fire the rear contact, at higher temperatures, so as to have the physical binding between the electrode current collector layer and the bottom of the p-type substrate. The firing process destroys the rear end layer and it ensures that metal makes contact with the p-type bulk. Now, you have got the rear sight and then you flip the whole set. Now, it is in the actual way you want it to be.

So, metal content, p-type layer you have the n-type and now, I have to grow these contacts at the top from which I will take out the electrons which are generated when the photons are incident on the solar cell. The front contact is also printed in the similar manner to that of the rear contact. So, you use a typical structure which you can use a mesh by which you are allowing the growth of these fingers. A pattern of line is used to prevent shading of the cell.

So, you use this lined pattern, so that the whole surface is not covered because if that happens and no light goes through. So, you use lines, so that light can also go through them. Then again, a furnace heats the cell to high temperature which ensures physical binding of the metal layer with the n-type layer and also removal of the volatile components. And the finished cell is now ready for encapsulations onto a module. So, now you can encapsulate these ready cells.

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So, till now, I have talked to you about the formation of these fingers. So, if you have seen the cross-sectional area, we have talked to you about the height, the width of these fingers. And nowhere, I have talked to you about the formation of this busbar and what is the requirement? Now, let me ask you a very simple question. If you have to collect the electron, which is going to flow through the external circuit, what will you do? You will have to connect each of these fingers with a wire.

So, you will have to connect each of these fingers with wires and then you will have to connect all these wires and then you will have to take it to the load and from the load they will go back again to the rear contact and then enter p-type, that will lead to serious problem of formation of contacts, you will have losses. And so, what was the way out? The way out is the fabrication of the busbar.

So, what happens all these fingers then go and get connected at the busbar and when you need to connect the wire which is going to allow the flow of the electron, you just need to make a connection right at one place and not at each and every finger. And that is why the requirement of busbar becomes extremely critical and to an extent essential.

Depending upon the, once I have the solar cells, depending upon the requirement whether I want constant current or I want constant voltage from each of the individual cell, I will choose whether I want to have a series connection of these cells or I want to talk about parallel connections.

In parallel connections, you have the output voltage is the sum of the voltages coming out from the cells we are considering. So, if you are considering three cells, V output is V_1 plus V_2 plus V_3 . In comparison, in parallel connection, what you will get V is equal to V_1 is equal to V_2 is equal to V_3 . But current in parallel connection will become equal to I equal to I_1 plus I_2 plus I_3 . So, depending upon the requirement, I will choose the configuration in which I will connect the solar cells which we have fabricated.

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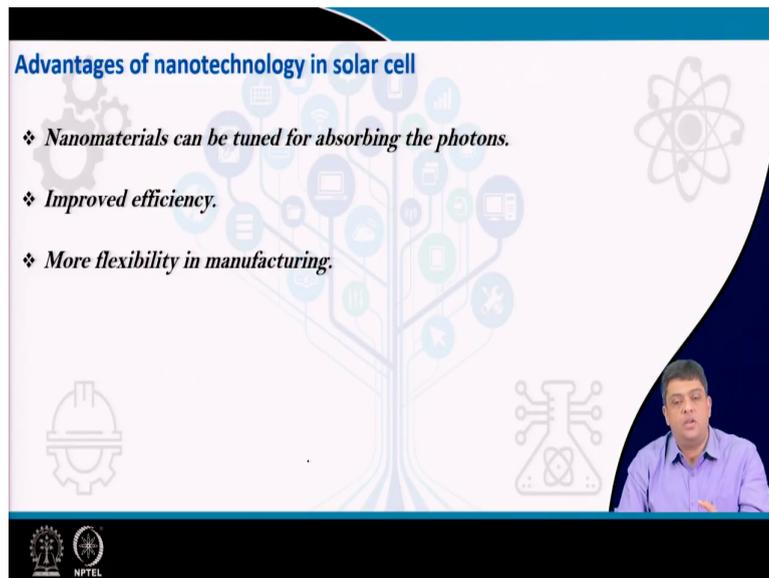
The slide is titled "Drawbacks in conventional solar technology". It features a central blue box with the text "Introduction of nanotechnology might be able to increase the efficiency of solar cells." A large red "BUT" is positioned below this box. To the left of the "BUT" are two orange boxes: "Low efficiency" and "Expensive to manufacturing", each with a red arrow pointing to it. A blue curved arrow points from the top box to the "BUT" box. The slide also includes a small video inset of a man in a purple shirt in the bottom right corner and the NPTEL logo in the bottom left corner.

The major drawbacks in the conventional solar technology continues to be low efficiency. And over the last few decades, nanotechnology has come into the picture and has improved the performance of these silicon based but conventional solar cells, but the cost still remains high because the use of nanotechnology adds certain of its own intrinsic cost factors. So, the cost still remains a major issue in making these solar cells a reality.

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Advantages of nanotechnology in solar cell

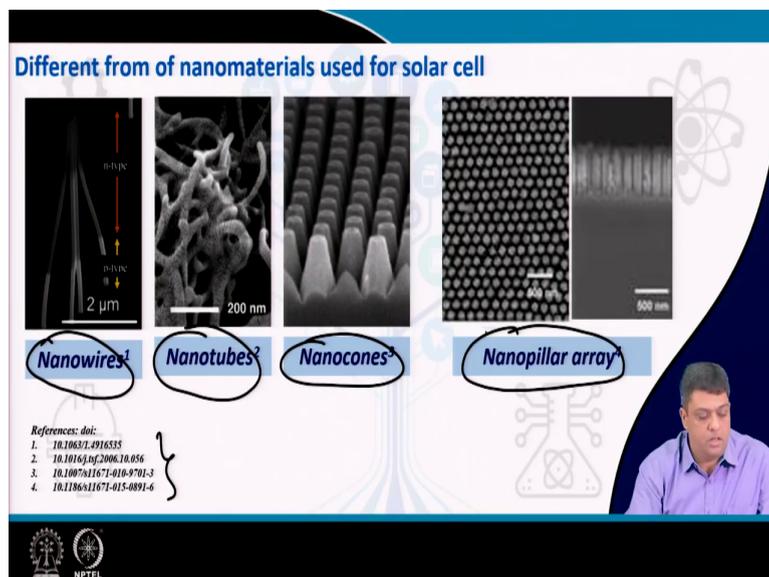
- ❖ *Nanomaterials can be tuned for absorbing the photons.*
- ❖ *Improved efficiency.*
- ❖ *More flexibility in manufacturing.*



So, although nanomaterials have come into picture and they have allowed to improve the efficiency, they have given flexibility in manufacturing and you can use various types of materials to absorb different types of photons. That means, you can work in different wavelength of frequency region of the solar spectrum. But still there are certain limitations which I just mentioned.

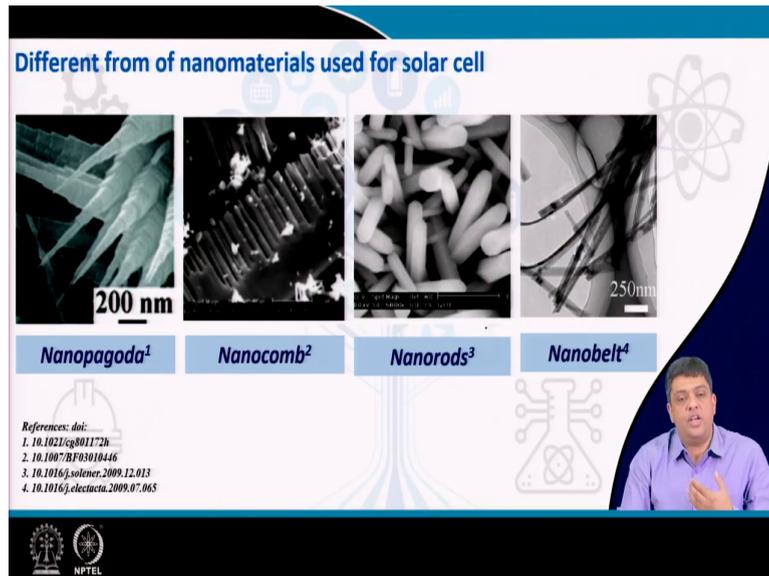
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Different form of nanomaterials used for solar cell



References: doi:

1. [10.1063/1.4916333](https://doi.org/10.1063/1.4916333)
2. [10.1016/j.nj.2006.10.056](https://doi.org/10.1016/j.nj.2006.10.056)
3. [10.1007/s11671-018-9781-3](https://doi.org/10.1007/s11671-018-9781-3)
4. [10.1186/s11671-015-0891-6](https://doi.org/10.1186/s11671-015-0891-6)



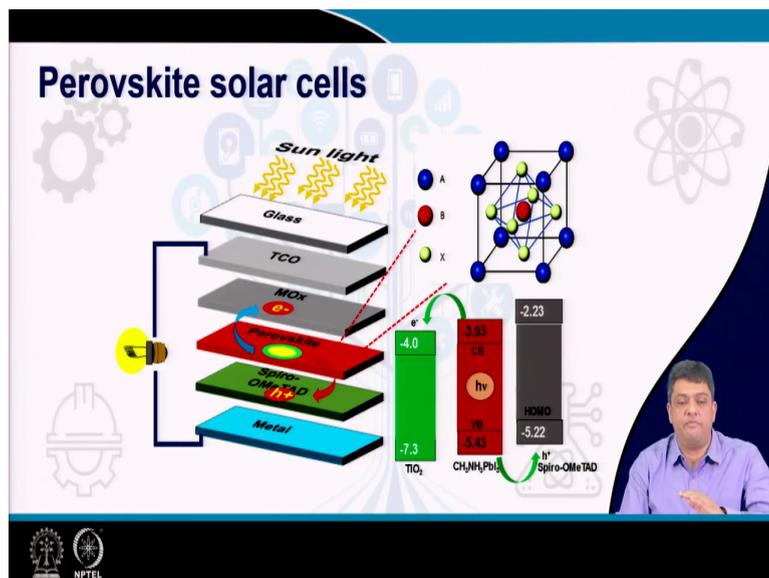
There are different types of nanomaterials now being used. These are the pictures which we have taken from literature, these are the doi's of the publications from which these pictures have been used for teaching purpose. And you can download the full article, if your institute allows and read the full article, which are mentioned here.

So, you can get nano wires, you can get nano tube, so you have tubular morphologies, you can get patterned nano cone structures, they allow improve performance by controlling absorption as well as ensuring controlled reflection of the light, you can have nanopillar arrays, you can have any other kind of structures, which we are talking about, which are slightly more complicated.

But the point I am making is that these structures allow improvement in the efficiencies and the absorption. So, what, where, and why they are leading to improvement? Please remember, the free electron module. So, what are you doing, is you are changing the unit cell which are leading to the formation of these kinds of structures.

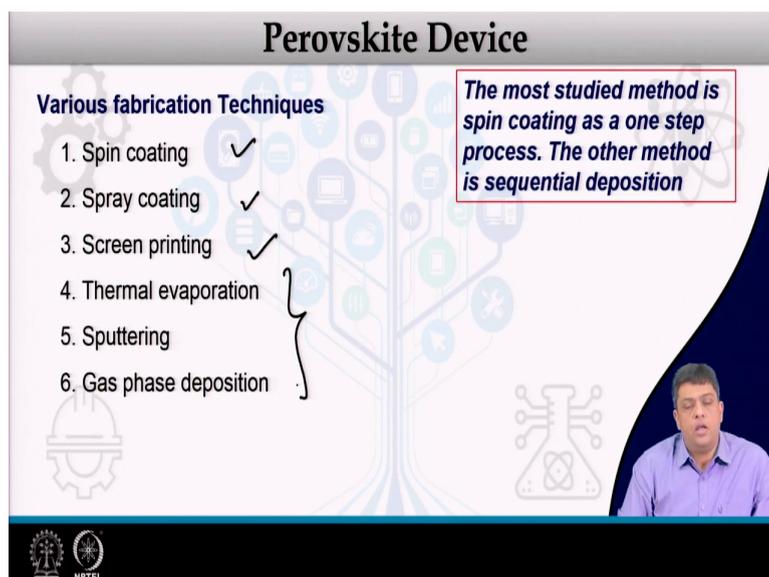
And once I change the lattice diameter a , the band gap can be tuned and along with the bandgap tuning, you can also tune the temperature range in which you want to work because the activation barrier and an activation energy in these kinds of materials also change as a function of lattice. This sentence which I just made if you want to understand more about it, please refer to any of the NPTEL course on physics of functional materials.

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Let us also because we are moving towards next generation devices, the most recent ones which we are talking about are on perovskite solar cells. I will talk to you more in detail about these cells in the next lecture. But today's lecture is based on fabrication techniques. So, let us see how these cells can be fabricated. The basic idea which you should remember for today's lecture is that you are going to use a perovskite-based material as the active material for performing the photo chemical or photo electrochemical based process.

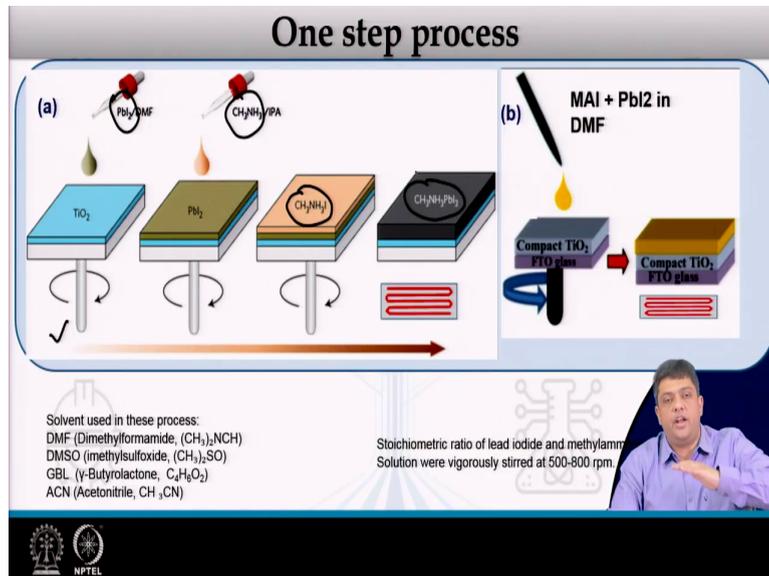
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So, to make a perovskite device, there are various fabrication techniques which are being used, most of them are very simple and straightforward to use, they include spin coating,

spray coating, screen printing, which we have just discussed, or slightly more involved techniques like thermal evaporation, sputtering, or gas phase deposition. And at the laboratory scale, the most studied method is spin coating, which is also one step process.

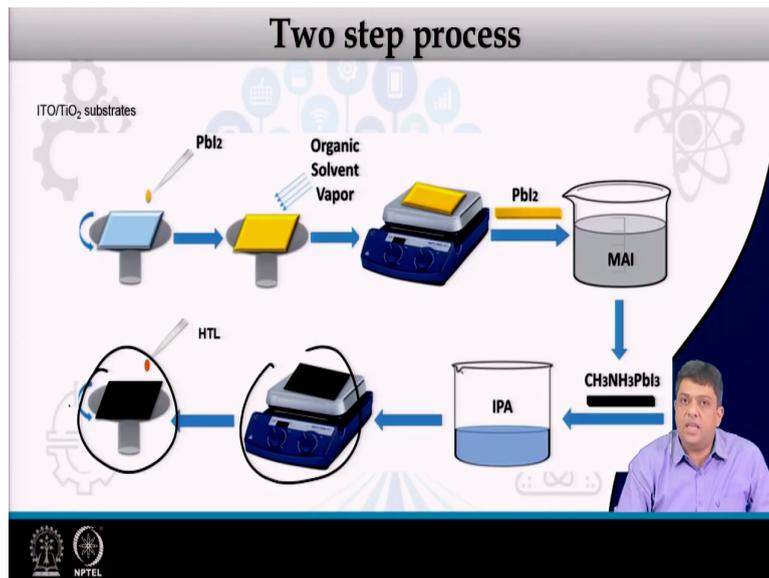
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So, what do you do in spin coating? Let us say I talked to you about the formation of a typical perovskite-based solar cell. So, you take a substrate and that substrate is spinning at certain speed, then you drop the precursors, which you want to deposit on these substrates which are spinning. Let us say I deposit TiO_2 on TiO_2 layer and then I deposit $\text{CH}_3\text{NH}_3\text{I}$. So, methyl ammonium iodide which is you have a solution methyl ammonium iodide in isopropanol alcohol and then you make a solution and then you drop cast.

So, you drop on top of PbI_2 then you can grow another layer of $\text{CH}_3\text{NH}_3\text{I}$, and these two react and what you get is methyl ammonium lead iodide which is a perovskite material. And this is the process of spin coating you can take this now device out and heat it and then you can get a compact device and then you can make the absorption layer on top of it or you can have a current collector at the base and some reflecting surfaces on the top.

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Similarly, you can have two step processes which involve formation in the first step and then again before the device is ready, you have to repeat the heating processes once again. So, these are two step processes, but these are the ones which are routinely being used to fabricate the perovskite cells in laboratory.

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- Solution-processed
One-step coating or Two-step coating
- Vacuum deposition

Pb source: PbI₂, PbCl₂, Pb(Ac)₂, Pb(NO₃)₂, PbO, Pb...
Organic source: MAI, FAI

MAI + PbI₂ -> MAPbI₃ ✓
3MAI + PbCl₂ -> MAPbI₃ + 2MACl ✓
MAI + PbI₂ + DMSO -> adduct -> MAPbI₃ ✓

PbI₂ (or PbO, Pb(NO₃)₂...) film -> dipping (or spin-coating) in MAI solution -> MAPbI₃ ✓

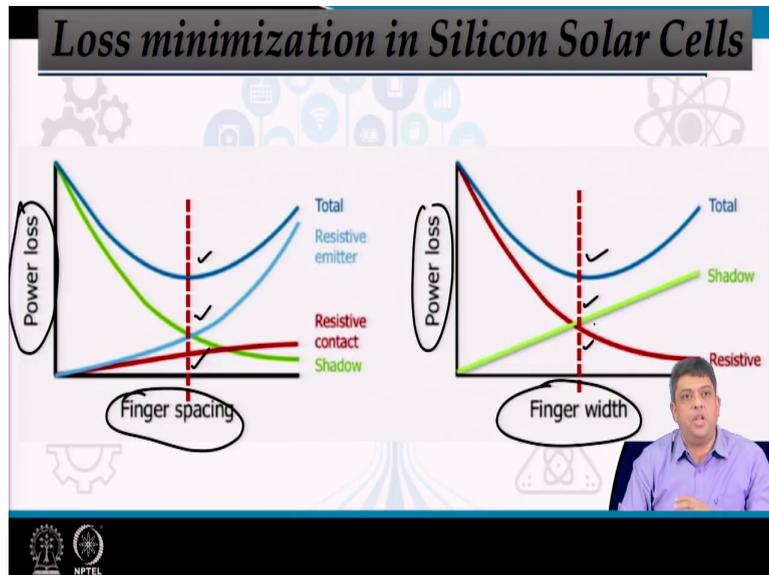
The other cations are
Formamidinium (FA)
Caesium (Cs)
Rubidium (Rb)

The other Anions are
Chlorine
Bromine
Iodine
And their combination in the precursor

And the detail reactions which take place are mentioned in this slide. So, if any one of you want to work in a lab and want to understand the growth process, then these are the reactions which take place and each and every step. You can use other cations or you can use other anions to replace iodine and then you will get various kinds of perovskite materials which are

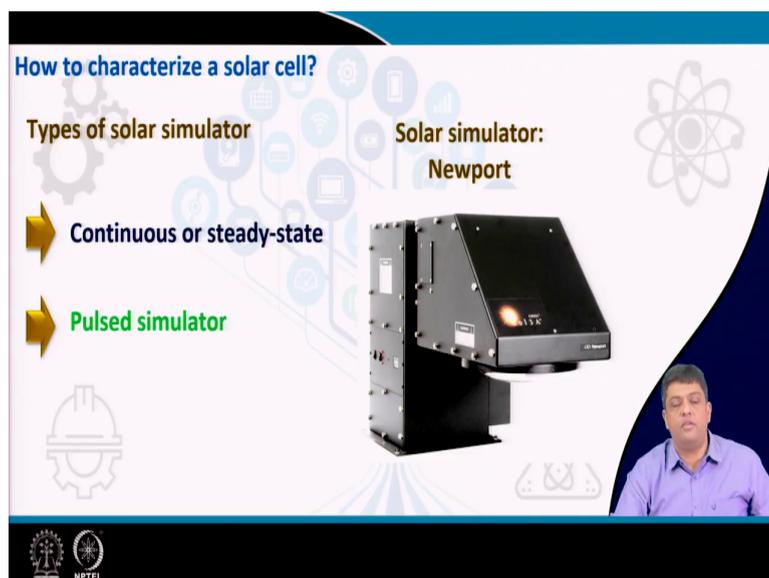
deposited on a substrate and then you can use the obtained cell for the application in the overall solar cell technology development.

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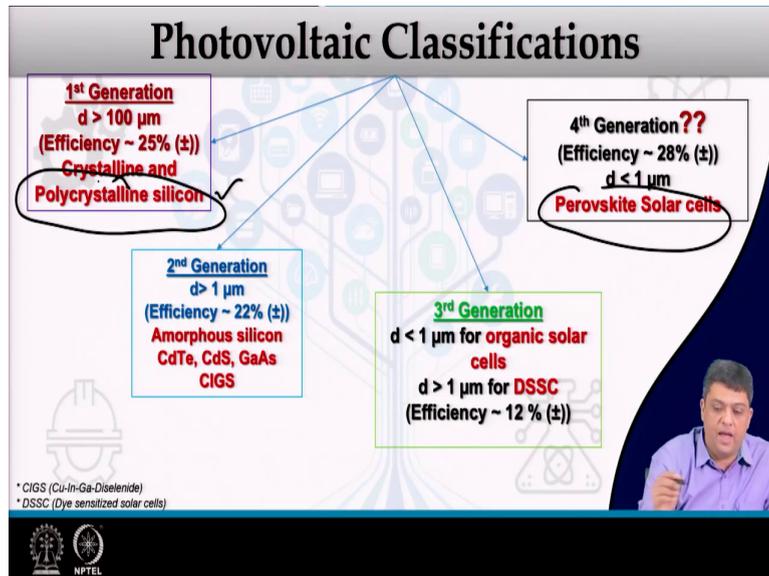
There are various reasons by which you can have losses, you can have losses due to shadow you can have losses due to resistive contacts. And so, depending upon the finger spacing and finger width you can plot the power losses and generally the size of the finger spacing and the size of the finger width is chosen, so that you can minimize the losses. So, that is the way you design the mesh, so that you can minimize the losses.

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And the typical processes by which you characterize these solar cells can be either continuous mode, where you are eliminating this cell continuously or pulsed simulator. Solar simulator from Newport, which is available in the institute and this photo has been taken from the website is the one which is shown in the figure.

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And you will now be able to understand the classification of photovoltaic cells. So, it depends on the type of materials because they have different efficiencies and the processes used to fabricate them are also slightly different.

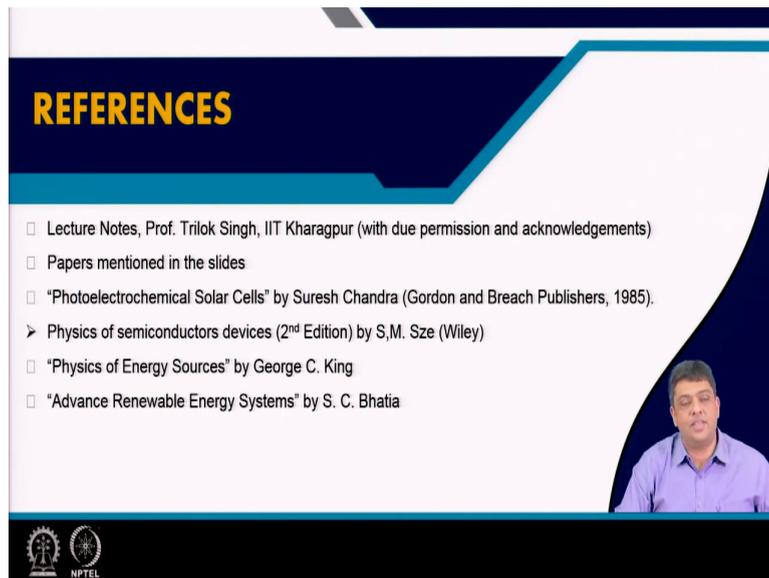
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CONCLUSION

- Fabrication processes to obtain different types of solar cells was discussed.
- The important of materials development was also introduced.

So, in today's lecture, what did we study, we studied the fabrication processes to obtain different types of solar cells. And we also discussed the importance of materials development for obtaining different types of solar cells.

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REFERENCES

- Lecture Notes, Prof. Trilok Singh, IIT Kharagpur (with due permission and acknowledgements)
- Papers mentioned in the slides
- "Photoelectrochemical Solar Cells" by Suresh Chandra (Gordon and Breach Publishers, 1985).
- Physics of semiconductor devices (2nd Edition) by S.M. Sze (Wiley)
- "Physics of Energy Sources" by George C. King
- "Advance Renewable Energy Systems" by S. C. Bhatia

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So, these are the references which were used to obtain the data and details which were presented in today's lecture. So, in the next lecture, we will give you the details of mathematical formulations. Those are used to understand the functioning of solar cells. I thank you for attending today's lecture.