Physics of Renewable Energy Systems
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Department of Physics
Indian Institute of Technology Kharagpur
Lecture 08
Characterization of Solar Cells and Future Direction

Welcome again to the course on Physics of Renewable Energy Systems. In the previous class, we discussed about the fabrication processes to obtain solar cells.

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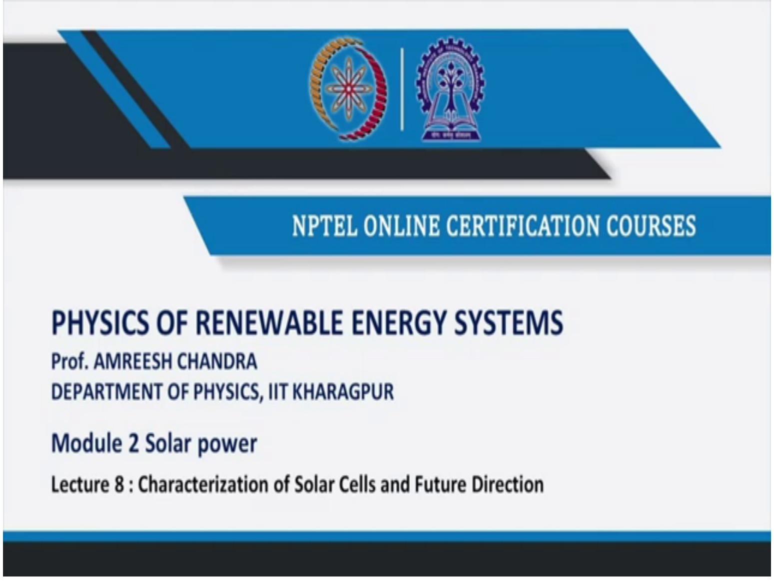

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PHYSICS OF RENEWABLE ENERGY SYSTEMS

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Module 2 Solar power

Lecture 8 : Characterization of Solar Cells and Future Direction

And in today's lecture, we will start our discussions on the characterization techniques or processes, which are used to understand the functioning of solar cells. And I will also like to give certain idea to you all about the future direction, which the research in this area or the development in this area will move. So, let us start our lecture today.

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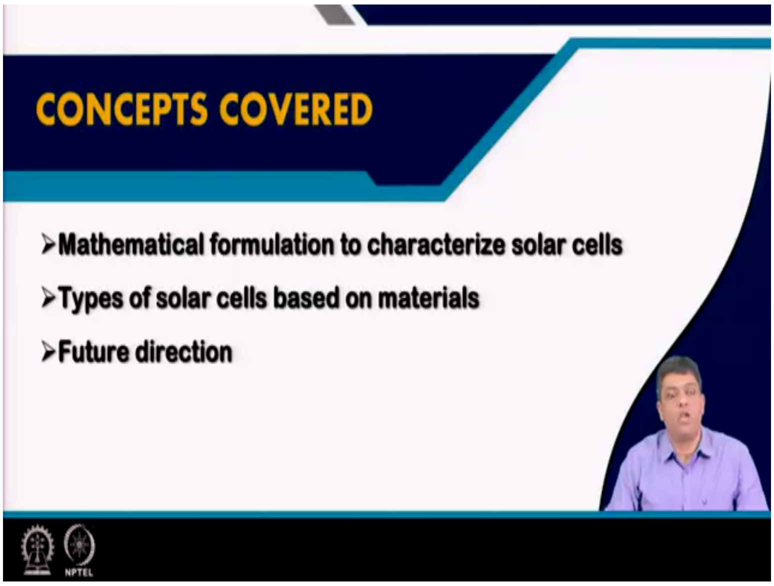

CONCEPTS COVERED

- Mathematical formulation to characterize solar cells
- Types of solar cells based on materials
- Future direction

So, in today's class, these are the concepts which we will cover, I will talk to you about the mathematical formulations, which are used to characterize solar cells. We will talk to you about the types of solar cells, which can be classified based on the materials that are used to obtain them and also the future direction in which this field is expected to move.

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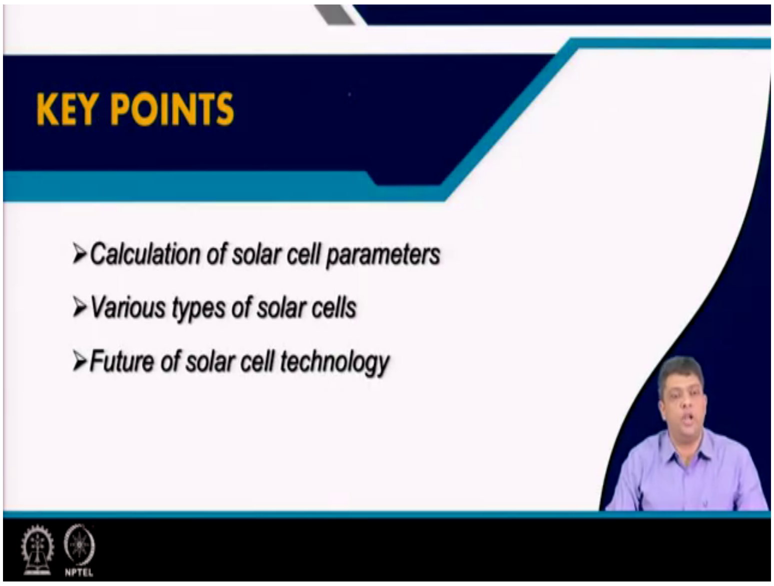

KEY POINTS

- *Calculation of solar cell parameters*
- *Various types of solar cells*
- *Future of solar cell technology*

And the key points, which you will understand after attending today's lecture would be the various processes or steps involved to calculate the parameters that are relevant to solar cells, what are the types of solar cells, and the future of solar cell technology.

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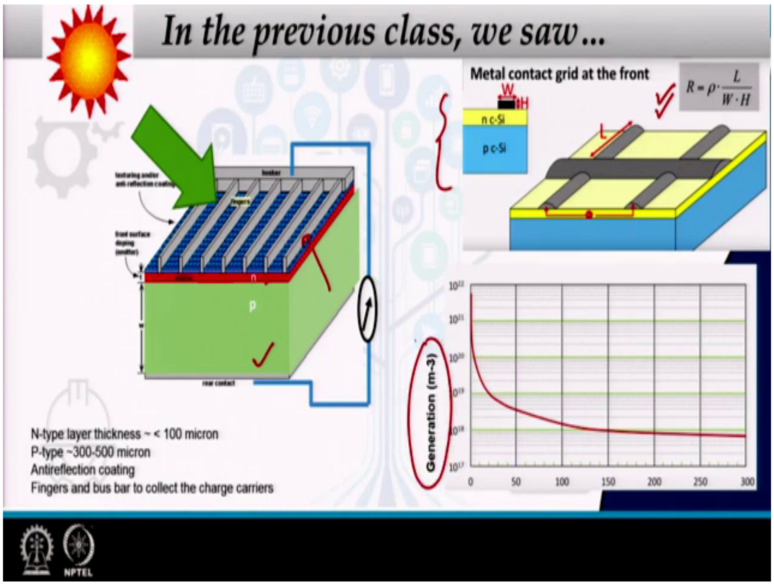

In the previous class, we saw...

N-type layer thickness ~ < 100 micron
P-type ~300-500 micron
Antireflection coating
Fingers and bus bar to collect the charge carriers

So, in the previous class, we have seen the fabrication of a typical silicon-based p-n junction solar cell, where you have a p-type layer and n-type layer and then you have the fingers which are fabricated on the top using the technique of screen printing. We have also talked to you about the process by which you can calculate the resistance of the whole surface or the layer which you are coating on top of it, which is of the conductive nature. And depending upon the thickness of the layer, you will have the generation of charge carriers.

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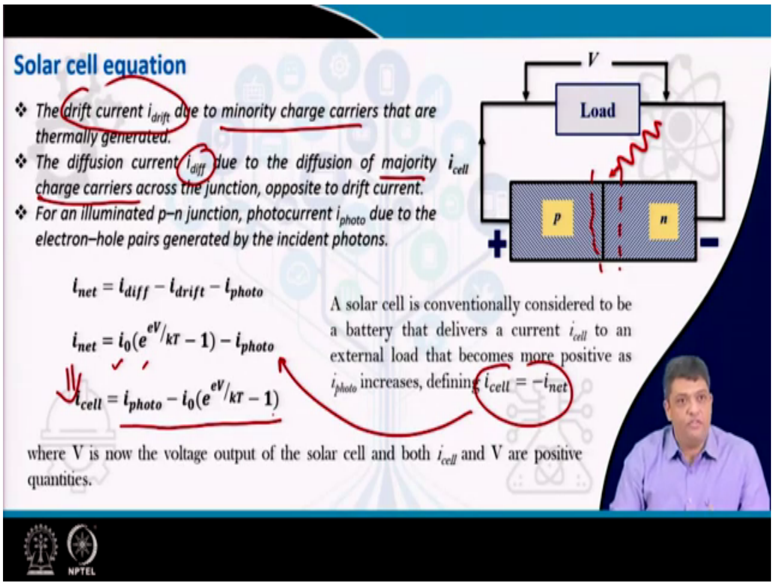

Solar cell equation

- The drift current i_{drift} due to minority charge carriers that are thermally generated.
- The diffusion current i_{diff} due to the diffusion of majority charge carriers across the junction, opposite to drift current.
- For an illuminated p–n junction, photocurrent i_{photo} due to the electron–hole pairs generated by the incident photons.

$$i_{net} = i_{diff} - i_{drift} - i_{photo}$$

$$i_{net} = i_0(e^{eV/kT} - 1) - i_{photo}$$

$$i_{cell} = i_{photo} - i_0(e^{eV/kT} - 1)$$

A solar cell is conventionally considered to be a battery that delivers a current i_{cell} to an external load that becomes more positive as i_{photo} increases, defining $i_{cell} = -i_{net}$

where V is now the voltage output of the solar cell and both i_{cell} and V are positive quantities.

So, when we were discussing about the formation of a p-n junction, we had talked to you about two concepts the formation of the drift current and the origin of diffusion current. Drift current is associated with, minority charge carriers whereas, diffusion current is associated with majority charge carriers. So, diffusion current is associated with the charges that flow across the junction whereas, the drift current is associated with the minority charge carriers which are obtained due to thermal energy.

Now, if I have a junction, and I illuminate it with solar radiation, I will obtain i photo which is also the photocurrent due to the electron hole pairs generated by incident photons, which have higher energy than the backup. So, you can calculate the net current which is equal to i diffusion minus i_{drift} minus i_{photo}.

Knowing the values of $i_{diffusion}$ and i_{drift} which was written in the earlier lectures. We can write i_{net} is equal to i_0, e raise to the power eV by kT minus 1 minus i_{photo}. Now, we know that a solar cell is conventionally considered to be a battery that delivers a current equal to i_{cell}, this current flows through the external load and it becomes more positive as i photo increases.

Therefore, you can write i_{cell} is equal to minus of i_{net} and if that is the case which we use, I will obtain the i_{cell} value which is equal to i_{photo} minus i_0 multiplied by e raise to the power of eV by kT minus 1 bracket, where V is now the voltage output of the solar cell and i_{cell} and V are both positive.

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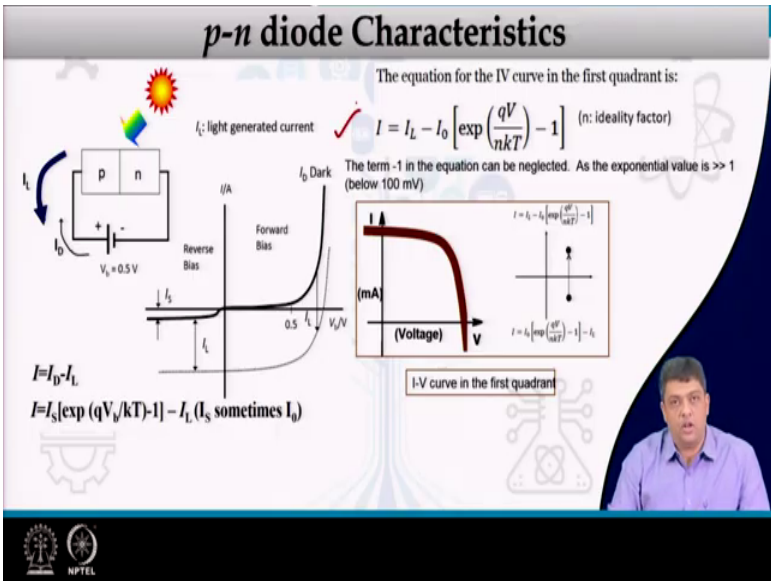

p-n diode Characteristics

The equation for the IV curve in the first quadrant is:

I_L: light generated current ✓ $$I = I_L - I_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right]$$ (n: ideality factor)

The term -1 in the equation can be neglected. As the exponential value is >> 1 (below 100 mV)

$I = I_D - I_L$

$I = I_S[\exp(qV_b/kT) - 1] - I_L$ (I_S sometimes I_0)

And just a quick reminder what we are doing, we are trying to understand the operation of a p-n junction. And using the first quadrant calculation that is used to determine the value of current, we know that the current in the first quadrant is given by I equals to I L that is load current minus I_0 exponential qV by nkT minus 1, where n is the ideality factor.

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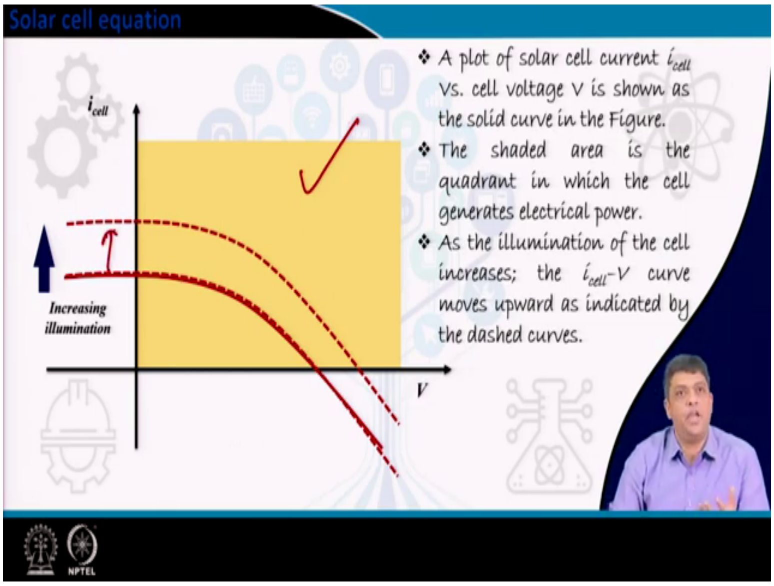

Solar cell equation

- A plot of solar cell current i_{cell} vs. cell voltage V is shown as the solid curve in the Figure.
- The shaded area is the quadrant in which the cell generates electrical power.
- As the illumination of the cell increases; the i_{cell}–V curve moves upward as indicated by the dashed curves.

So, what happens, let us draw i_{cell} versus voltage curve, you find that the shaded area is the quadrant in which the cell generates the electrical power. So, you are working in the area, the quadrant in which the cell generates electrical power. As the illumination of the cell increases, the i_{cell} minus V curve moves upward as indicated by the dashed line. So, you have more current being obtained due to the illumination of the cell and that is what is expected from a solar cell.

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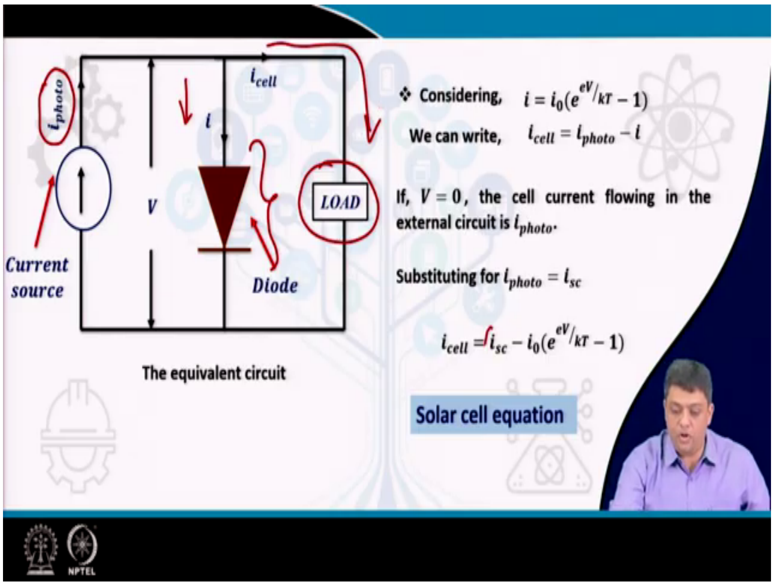

- Considering, $i = i_0(e^{eV/kT} - 1)$

  We can write, $i_{cell} = i_{photo} - i$

If, $V = 0$, the cell current flowing in the external circuit is i_{photo}.

Substituting for $i_{photo} = i_{sc}$

$$i_{cell} = i_{sc} - i_0(e^{eV/kT} - 1)$$

Solar cell equation

The equivalent circuit

So, the equivalent circuit for the solar cell can be drawn. What are we trying to draw? We are trying to reduce the complete device into certain electrical components. So, we have flow of photocurrent the diode which diode are we talking about the p-n junction that is falling and then a load. If there is no load, what will happen, you will get what kind of current? You will get the short circuit current, if you connect the wire through.

So, considering i is equal to i_0 e raise to power eV by kT minus 1 and knowing the relation that i_{cell} is equal to i_{photo} minus i. And if v is equal to 0, the cell current flowing in the external circuit is i photo. So, there is voltage across the diode is 0, then the cell current flowing in the external circuit will be equal to i photo because there will be no current flowing in this direction and then the i photo will become available to the load.

So, if you substitute i_{photo} as i_{short} circuit current, then you get i_{cell} is equal to i_{short} circuit current minus i_0 into e raise to power eV by kT minus 1. And this gives you the solar cell equation and also gives you the mathematical formulations to determine the current which will be flowing through the cell. So, before you start characterizing the solar cell, you must find out what is the short circuit current and the open circuit voltage.

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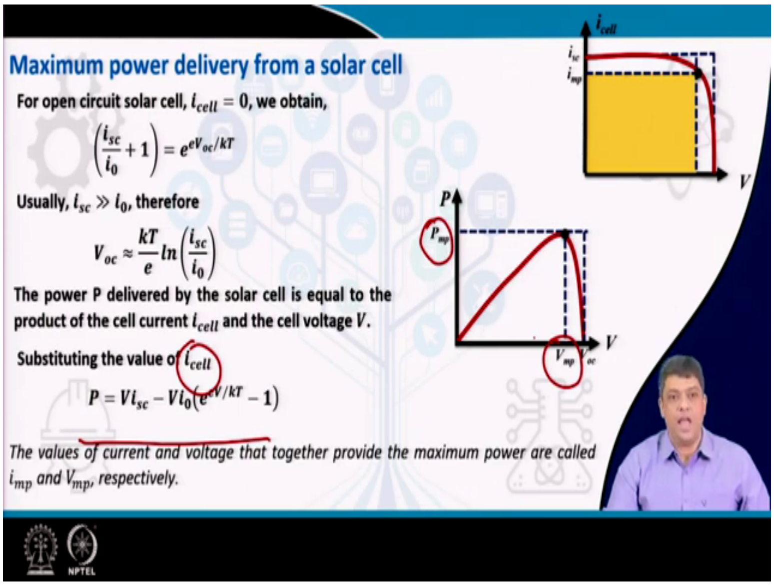

Maximum power delivery from a solar cell

For open circuit solar cell, $i_{cell} = 0$, we obtain,

$$\left(\frac{i_{sc}}{i_0} + 1\right) = e^{eV_{oc}/kT}$$

Usually, $i_{sc} \gg i_0$, therefore

$$V_{oc} \approx \frac{kT}{e} ln\left(\frac{i_{sc}}{i_0}\right)$$

The power P delivered by the solar cell is equal to the product of the cell current i_{cell} and the cell voltage V.

Substituting the value of i_{cell}

$$P = Vi_{sc} - Vi_0(e^{eV/kT} - 1)$$

The values of current and voltage that together provide the maximum power are called i_{mp} and V_{mp}, respectively.

Let us now see what is the maximum power which can be delivered by a solar cell. From the open circuit condition, we have i_{cell} is equal to 0. So, we obtain that i_{sc} by i_0 plus 1 is equal to e raise to power eV_{oc} by kT, because we have the open circuit and we get the open circuit voltage. Now, generally, the short circuit current is much larger than the initial current i_0.

And therefore, V_{oc} is approximately equal to kT by e ln of i_{sc} by i_0. And the power delivered by the cell is equal to the product of the cell current that is i_{cell} and the cell voltage V. We have already estimated the value of i cell. So, substituting the value of i_{cell} you can get that power is equal to V into i_{sc} minus voltage i_0 into e raise to power eV by kT minus 1. So, this is the maximum power which you get from the cell.

So, there are two things which you will see, you have P_{mp} and V_{mp}. What is the meaning? The values of current and voltage that together provide the maximum power are called as i_{mp} and V_{mp}. So, these are the two values which are used to obtain the maximum power.

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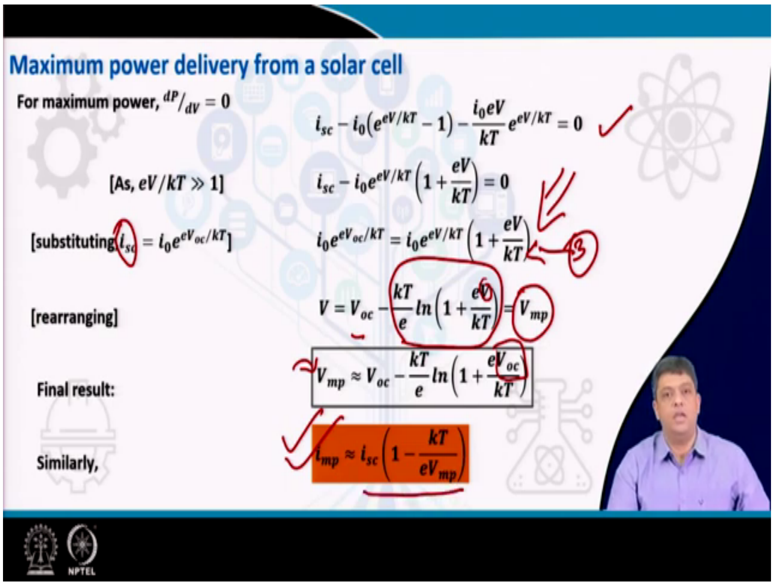

Maximum power delivery from a solar cell

For maximum power, $^{dP}/_{dV} = 0$

$$i_{sc} - i_0\left(e^{eV/kT} - 1\right) - \frac{i_0 eV}{kT} e^{eV/kT} = 0$$

[As, $eV/kT \gg 1$]

$$i_{sc} - i_0 e^{eV/kT}\left(1 + \frac{eV}{kT}\right) = 0$$

[substituting $i_{sc} = i_0 e^{eV_{oc}/kT}$]

$$i_0 e^{eV_{oc}/kT} = i_0 e^{eV/kT}\left(1 + \frac{eV}{kT}\right) \quad ③$$

[rearranging]

$$V = V_{oc} - \frac{kT}{e} ln\left(1 + \frac{eV}{kT}\right) = V_{mp}$$

Final result:

$$\boxed{V_{mp} \approx V_{oc} - \frac{kT}{e} ln\left(1 + \frac{eV_{oc}}{kT}\right)}$$

Similarly,

$$\boxed{i_{mp} \approx i_{sc}\left(1 - \frac{kT}{eV_{mp}}\right)}$$

We can look into the same thing once again. So, the maximum power is dP by dV and if you use the initial formulation which we had started using the short circuit current and the i photo and i_{cell}, you will find that as eV by kT is much greater than 1, you can reduce this equation to the form that i_{sc} minus i 0 e raise to power eV by kT into 1 plus eV by kT.

Now, you can substitute in this formulation the value of short circuit current which was derived earlier and if you do so, then you get equation number 3. So, I now have a relation between the short circuit current in terms of i_0. Let us rearrange and if we can rearrange you will get that the value of V_{mp} is equal to V_0 that is the open circuit voltage with reduced by a factor kT by e ln 1 plus eV by kT.

And the final result is that V_{mp} is approximately equal to V_{oc} minus kT by e ln 1 plus in eV_{oc} by kT. So, this is the value where you have replaced V by V_{oc} and that gives you the maximum power that can be delivered from solar cell. This was the process by which you determine the value of V_{mp}. And similarly, we can also derive the value of i_{mp} that is the current value which has to be used to obtain the maximum power from a solar cell and that is equal to i_{sc} into 1 minus kT by eV_{mp}.

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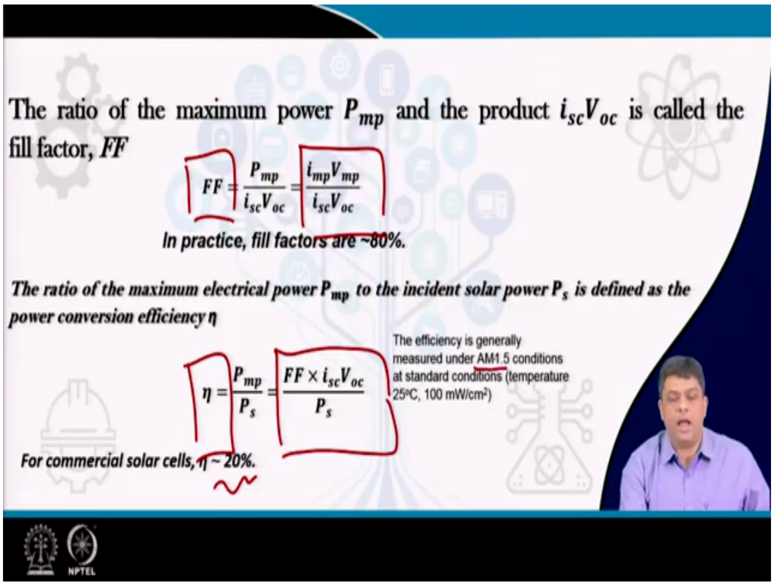

The ratio of the maximum power P_{mp} and the product $i_{sc}V_{oc}$ is called the fill factor, *FF*

$$FF = \frac{P_{mp}}{i_{sc}V_{oc}} = \frac{i_{mp}V_{mp}}{i_{sc}V_{oc}}$$

In practice, fill factors are ~80%.

The ratio of the maximum electrical power P_{mp} to the incident solar power P_s is defined as the power conversion efficiency η

$$\eta = \frac{P_{mp}}{P_s} = \frac{FF \times i_{sc}V_{oc}}{P_s}$$

The efficiency is generally measured under AM1.5 conditions at standard conditions (temperature 25°C, 100 mW/cm²)

For commercial solar cells, η ~ 20%.

So, the ratio of the maximum power P_{mp} and the product i_{sc} and V_{oc} is called the fill factor and it is given as P_{mp} by i_{sc} by V_{oc} and denoted by FF. This is equal to i_{mp} into V_{mp} divided by i_{sc} by V_{oc}. In practice, the fill factors are approximately 80 percent because of physical restrictions in the design.

In comparison to the fill factor, the ratio of maximum electrical power to the incident solar power defines the power conversion efficiency, which is given as P_{mp} by P_s and that is equal to FF into i_{sc} V_{oc} divided by P_s. So, these are the two terms which are routinely used to explain the parameters associated with the solar cell.

For commercial solar cells, which are available in the market, their efficiencies are approximately 20 percent plus minus and generally the efficiencies which are reported are under the conditions of AM 1.5 and temperature of 25 degrees and power of 100 milliwatts per centimetre square.

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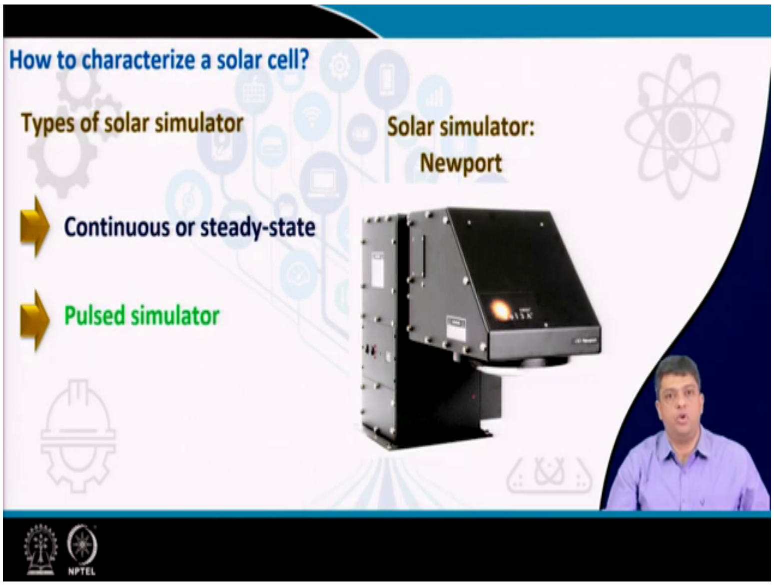
How to characterize a solar cell?

Types of solar simulator

- Continuous or steady-state
- Pulsed simulator

Solar simulator:
Newport

So, how do we characterize a solar cell, we again characterize these solar cells. Now, if I have to obtain the values of sc or V_{oc} under different energies under different radiation conditions, then I use a solar simulator, where I can change the intensity, I can change the time for which the radiation is available, and I can change various factors and then I can find out the parameters which are going to change in a given solar cell.

So, either you can characterize these solar cells under continuous or steady state mode or you can also have pulsed simulators that you have appearance of radiation and as pulses. So, for sometimes they are there when you switch off then you switch on then you switch off and then you see how the cells are responding. And this is what a typical solar simulator from Newport looks like.

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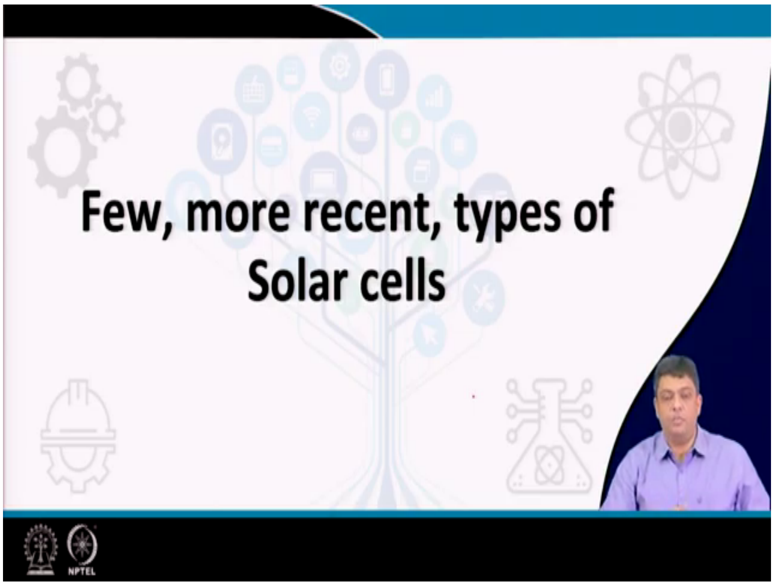

Few, more recent, types of Solar cells

Let us see a few more recent types of solar cells which are being mentioned just to show that although you have new generation of solar cells, but the characterization and the mathematical formulations, which are used to explain the operation of these solar cells, they remain the same.

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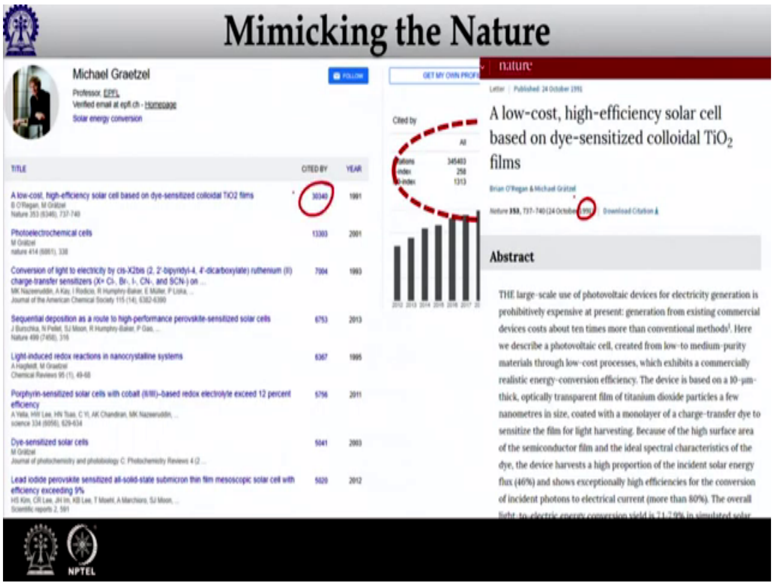

Mimicking the Nature

Michael Graetzel
Professor, EPFL
Verified email at epfl.ch - Homepage
Solar energy conversion

TITLE	CITED BY	YEAR
A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO2 films B O'Regan, M Grätzel Nature 353 (6346), 737-740	30340	1991
Photoelectrochemical cells M Grätzel nature 414 (6861), 338	13303	2001
Conversion of light to electricity by cis-X2bis (2, 2'-bipyridyl-4, 4'-dicarboxylate) ruthenium (II) charge-transfer sensitizers (X= Cl-, Br-, I-, CN-, and SCN-) on ... MK Nazeeruddin, A Kay, I Rodicio, R Humphry-Baker, E Müller, P Liska, ... Journal of the American Chemical Society 115 (14), 6382-6390	7004	1993
Sequential deposition as a route to high-performance perovskite-sensitized solar cells J Burschka, N Pellet, SJ Moon, R Humphry-Baker, P Gao, ... Nature 499 (7458), 316	6753	2013
Light-induced redox reactions in nanocrystalline systems A Hagfeldt, M Graetzel Chemical Reviews 95 (1), 49-68	6367	1995
Porphyrin-sensitized solar cells with cobalt (II/III)–based redox electrolyte exceed 12 percent efficiency A Yella, HW Lee, HN Tsao, C Yi, AK Chandiran, MK Nazeeruddin, ... science 334 (6056), 629-634	5756	2011
Dye-sensitized solar cells M Grätzel Journal of photochemistry and photobiology C: Photochemistry Reviews 4 (2 ...	5041	2003
Lead iodide perovskite sensitized all-solid-state submicron thin film mesoscopic solar cell with efficiency exceeding 9% HS Kim, CR Lee, JH Im, KB Lee, T Moehl, A Marchioro, SJ Moon, ... Scientific reports 2, 591	5020	2012

nature

Letter | Published: 24 October 1991

A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO_2 films

Brian O'Regan & Michael Grätzel

Nature 353, 737–740 (24 October 1991) | Download Citation

Abstract

THE large-scale use of photovoltaic devices for electricity generation is prohibitively expensive at present: generation from existing commercial devices costs about ten times more than conventional methods[1]. Here we describe a photovoltaic cell, created from low-to medium-purity materials through low-cost processes, which exhibits a commercially realistic energy-conversion efficiency. The device is based on a 10-μm-thick, optically transparent film of titanium dioxide particles a few nanometres in size, coated with a monolayer of a charge-transfer dye to sensitize the film for light harvesting. Because of the high surface area of the semiconductor film and the ideal spectral characteristics of the dye, the device harvests a high proportion of the incident solar energy flux (46%) and shows exceptionally high efficiencies for the conversion of incident photons to electrical current (more than 80%). The overall light-to-electric energy conversion yield is 7.1-7.9% in simulated solar

So, the first one was given by Michael Graetzel and that was the dye sensitized solar cells, where the Graetzel group try to mimic the nature. And it was reported in 1991. And if you look into the kind of citations they have, it is more than 30,000 people have referred to this paper in their own publication. So, it brought a new generation of solar cells into reality.

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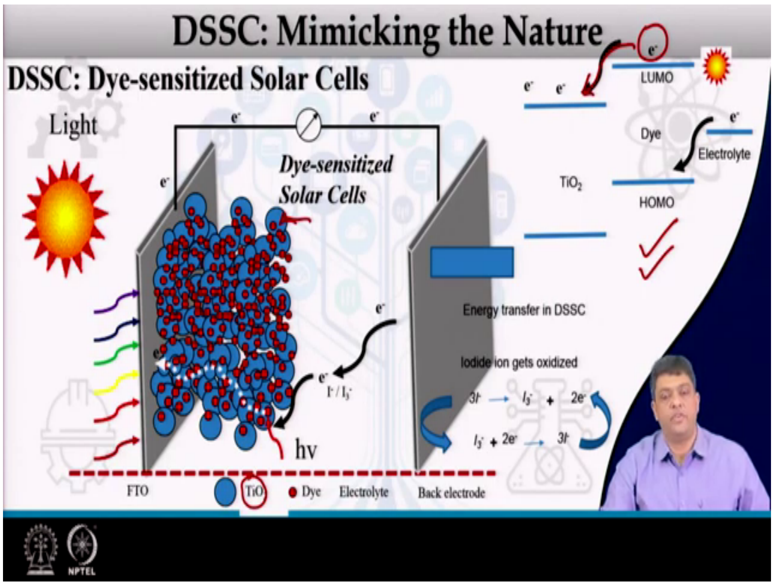

DSSC: Mimicking the Nature

DSSC: Dye-sensitized Solar Cells

Energy transfer in DSSC

Iodide ion gets oxidized

$3I^- \rightarrow I_3^- + 2e^-$

$I_3^- + 2e^- \rightarrow 3I^-$

So, what do they do here? They use a dye and which is on top of a semiconductor and then they have the electrodes and on elimination of light which crosses the transparent layer, you have the drop of electron to the semiconductor and then you have the condition where the higher level is populated. So, when you have the electrons in the semiconductors which can take part in the conduction mechanisms and the whole process is facilitated by using a Redox Based Electrolytes. So, this was a typical dye sensitized solar cell.

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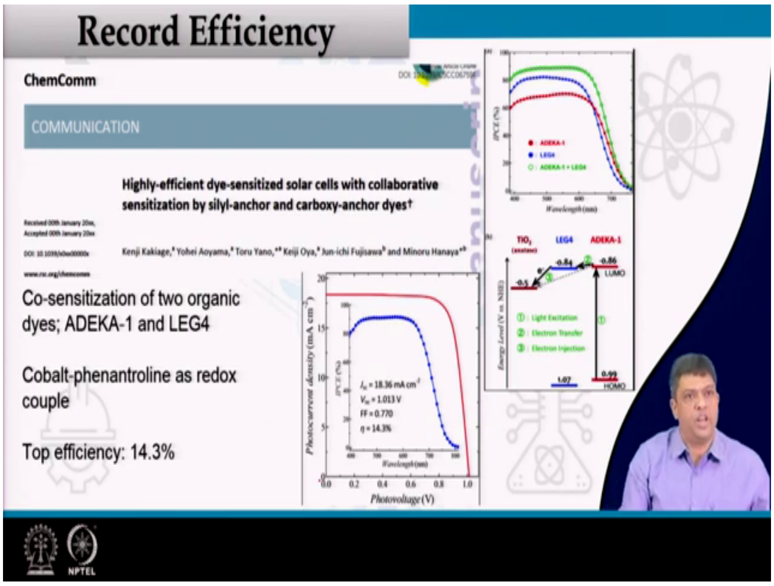

Record Efficiency

ChemComm

COMMUNICATION

Highly-efficient dye-sensitized solar cells with collaborative sensitization by silyl-anchor and carboxy-anchor dyes†

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www.rsc.org/chemcomm

Kenji Kakiage,ᵃ Yohei Aoyama,ᵃ Toru Yano,*ᵃ Keiji Oya,ᵃ Jun-ichi Fujisawaᵇ and Minoru Hanaya*ᵇ

Co-sensitization of two organic dyes; ADEKA-1 and LEG4

Cobalt-phenantroline as redox couple

Top efficiency: 14.3%

And there are a lot of reports which have been coming out in literature. And very recently you have seen, we have seen that the top efficiencies in die synthesize solar cells have reached to approximately 14 percent.

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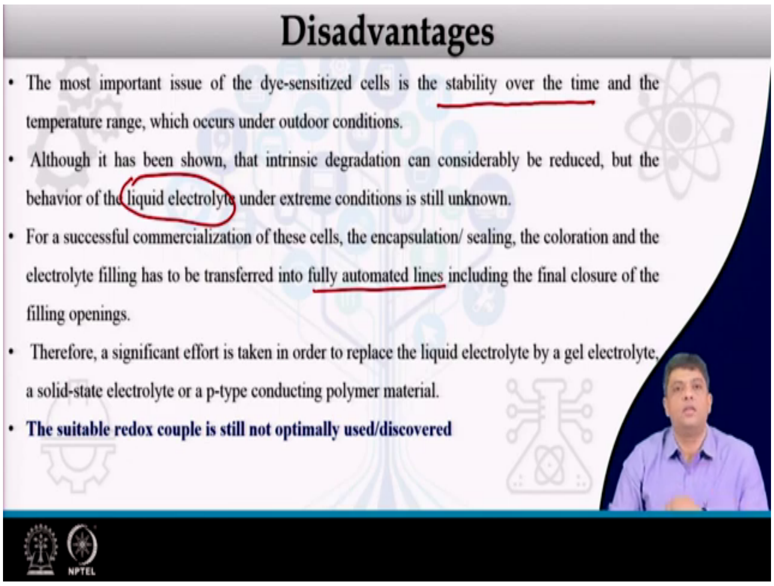

Disadvantages

- The most important issue of the dye-sensitized cells is the stability over the time and the temperature range, which occurs under outdoor conditions.
- Although it has been shown, that intrinsic degradation can considerably be reduced, but the behavior of the liquid electrolyte under extreme conditions is still unknown.
- For a successful commercialization of these cells, the encapsulation/ sealing, the coloration and the electrolyte filling has to be transferred into fully automated lines including the final closure of the filling openings.
- Therefore, a significant effort is taken in order to replace the liquid electrolyte by a gel electrolyte, a solid-state electrolyte or a p-type conducting polymer material.
- **The suitable redox couple is still not optimally used/discovered**

But they have some major limitations which have to be countered before they become available for large scale use. And the first one is how to ensure their stability over long time duration along with that, you also have to ensure that they can be operated in different temperature zones. So, you have to find ways to make these DSSCs to work for long durations as well as in varying temperature conditions.

Now, as you change the conditions, although the degradation of the active material may be low, but then comes the problem of degradation of the liquid electrolyte. So, a lot of work needs to be done on understanding to the processes by which you can control the degradation of liquid electrolytes, which take part in the redox mechanisms that lead to electron transfer. Still, you have to standardize processes by which you can make fully automated lines to obtain the sense. So, a lot of work still needs to be performed before DSSCs becomes a reality.

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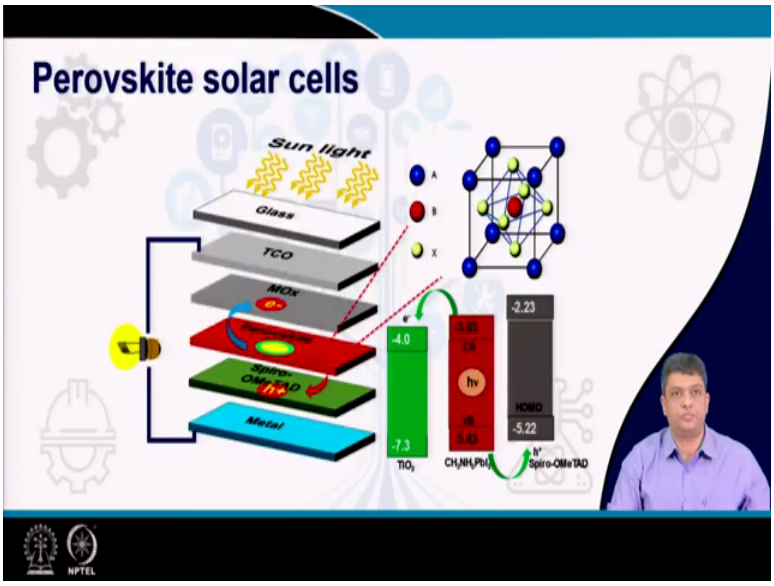
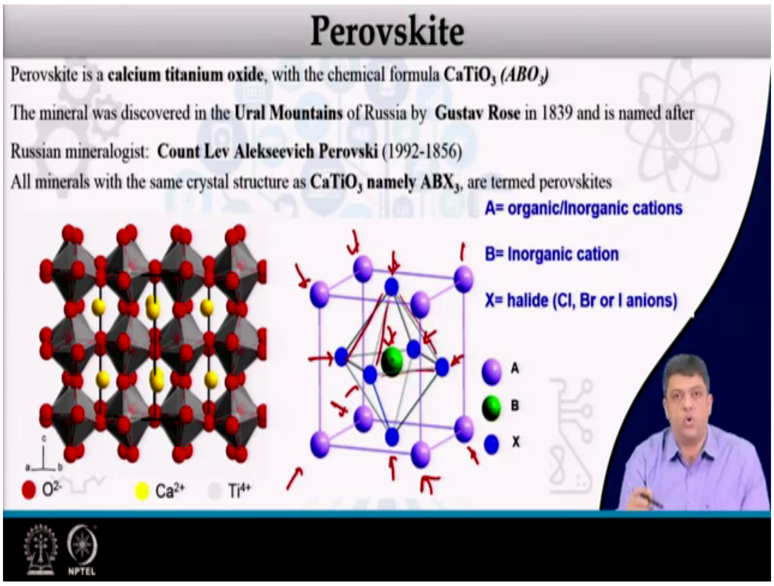


Perovskite solar cells



Perovskite

Perovskite is a **calcium titanium oxide**, with the chemical formula **$CaTiO_3$** *(ABO_3)*

The mineral was discovered in the **Ural Mountains** of Russia by **Gustav Rose** in 1839 and is named after

Russian mineralogist: **Count Lev Alekseevich Perovski** (1992-1856)

All minerals with the same crystal structure as **$CaTiO_3$ namely ABX_3**, are termed perovskites

A= organic/Inorganic cations

B= Inorganic cation

X= halide (Cl, Br or I anions)

Similarly, we have the discovery of perovskite based solar cells and what are these solar cells. These perovskite solar cells are the ones which use materials which have a perovskite structure. And if you just want to know the history of this word perovskite, it came in after the Russian Mineralogist Perovskite and what it happened that the mineralogists, they studied the structure of calcium titanium oxide and you have a structure which is called as ABX_3.

So, what happens in this structure? The A type organic or inorganic cations they occupy the cube edges, the B type inorganic cotton occupies the body center whereas, the X halides they occupy the face centres. In conventional perovskites it was called as ABO_3, but the perovskite which we are using in our solar cells, these are ABX_3 types of cells and you see this structure which is there it forms an octahedra.

So, it is called an X halide octahedra here, otherwise conventionally, it was called an oxygen octahedra. So, you had an octahedra where the organic cation was, inorganic cotton was sitting at the center.

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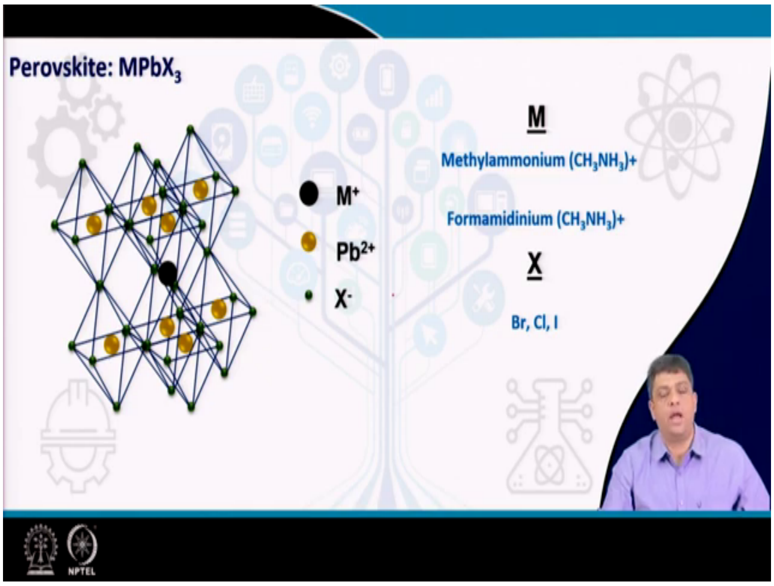

Perovskite: $MPbX_3$

- ● M^+
- ● Pb^{2+}
- ● X^-

M

Methylammonium $(CH_3NH_3)+$

Formamidinium $(CH_3NH_3)+$

X

Br, Cl, I

So, let us see how does it look. So, you had a unit cell then you arrange this unit cell in a lattice at the cube by edges or in these edges of these octahedra you have the atoms where the black atom is your M plus, the yellow atoms which we are showing in this slide are representing the lead atoms, and the small dots which at the coordinates of these octahedra are your X halides.

So, you can choose different types of organic or in organic ions whereas, X atoms are either bromide or chloride or iodide. So, these are the typical anions or cations, which we are using to fabricate these perovskite structures.

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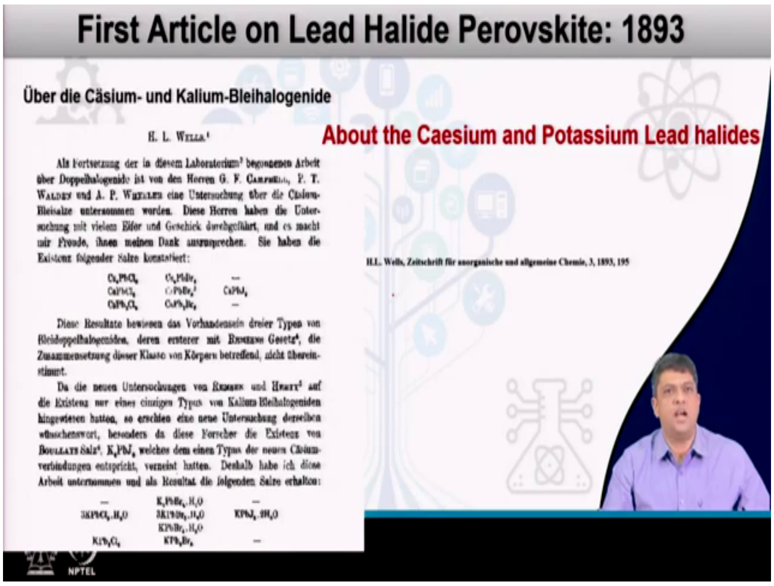


First Article on Lead Halide Perovskite: 1893

Über die Cäsium- und Kalium-Bleihalogenide

H. L. Wells[1]

Als Fortsetzung der in diesem Laboratorium[2] begonnenen Arbeit über Doppelhalogenide ist von den Herren G. F. Campbell, P. T. Walden und A. P. Wheeler eine Untersuchung über die Cäsium-Bleisalze unternommen worden. Diese Herren haben die Untersuchung mit vielem Eifer und Geschick durchgeführt, und es macht mir Freude, ihnen meinen Dank auszusprechen. Sie haben die Existenz folgender Salze konstatiert:

Cs_4PbCl_6 Cs_4PbBr_6 —
$CsPbCl_3$ $CsPbBr_3$[3] $CsPbJ_3$
$CsPb_2Cl_5$ $CsPb_2Br_5$ —

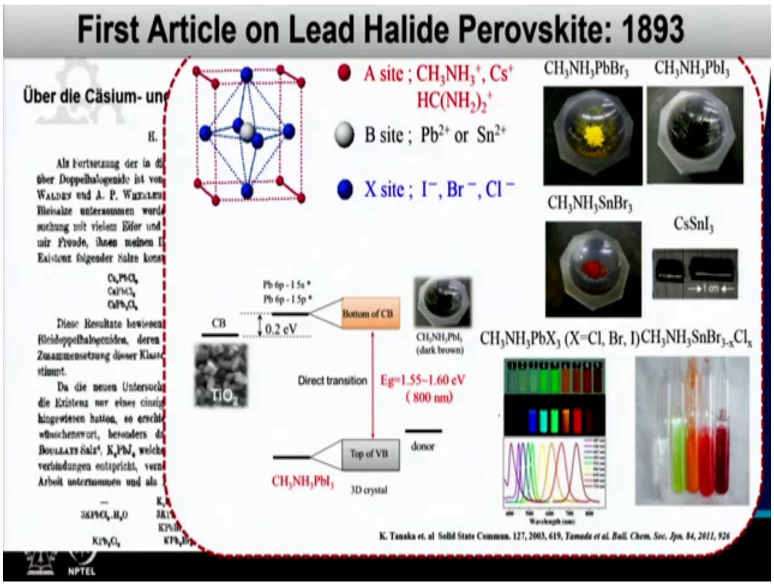
Diese Resultate bewiesen das Vorhandensein dreier Typen von Bleidoppelhalogeniden, deren ersterer mit Remsens Gesetz[4], die Zusammensetzung dieser Klasse von Körpern betreffend, nicht übereinstimmt.

Da die neuen Untersuchungen von Remsen und Herty[5] auf die Existenz nur eines einzigen Typus von Kalium-Bleihalogeniden hingewiesen hatten, so erschien eine neue Untersuchung derselben wünschenswert, besonders da diese Forscher die Existenz von Boullays Salz[6], K_4PbJ_6, welches dem einen Typus der neuen Cäsiumverbindungen entspricht, verneint hatten. Deshalb habe ich diese Arbeit unternommen und als Resultat die folgenden Salze erhalten:

— $K_4PbBr_6.H_2O$ —
$3KPbCl_3.H_2O$ $3KPbBr_3.H_2O$ $KPbJ_3.2H_2O$
$KPbBr_3.H_2O$
KPb_2Cl_5 KPb_2Br_5 —

About the Caesium and Potassium Lead halides

H.L. Wells, Zeitschrift für anorganische und allgemeine Chemie, 3, 1893, 195



First Article on Lead Halide Perovskite: 1893

- A site ; $CH_3NH_3^+$, Cs^+ $HC(NH_2)_2^+$
- B site ; Pb^{2+} or Sn^{2+}
- X site ; I^-, Br^-, Cl^-

K. Tanaka et. al Solid State Commun. 127, 2003, 619, *Tamada et al. Bull. Chem. Soc. Jpn. 84, 2011, 926*

And the first article came in 1893. And in today's area we have been using, let us say methyl ammonium lead bromide or iodides, which can be fabricated using a simple motor vessel-based synthesis protocol. So, you can use the precursors on a motor vessel and then make a solid solution out of these precursors.

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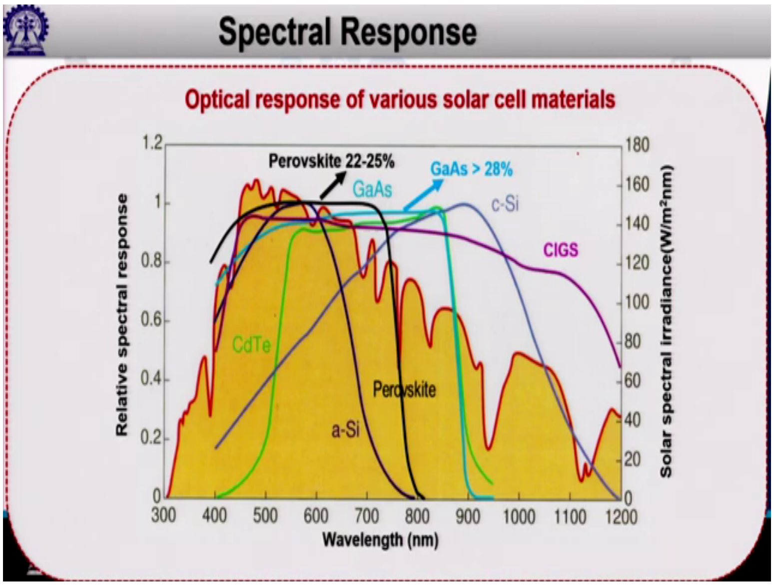

Spectral Response

Optical response of various solar cell materials

The advantage of these perovskite solar cells are that they have allowed an area which is much larger than silicon cells to absorb the wavelengths and the relative spectral response is also quite high compared to the amorphous silicon or silicon-based technologies which are being used. And already we have perovskite based solar cells, which are reporting efficiencies of 22 to 25 percent.

They are easy to fabricate, they are easy to understand and they are also easy to obtain in large scale. Along with that, they have large shelf life and the synthesis protocols to obtain the solar cells are also much simpler. And therefore, these perovskites based solar cells are expected to bring in significant cost reduction in the whole solar cell technology.

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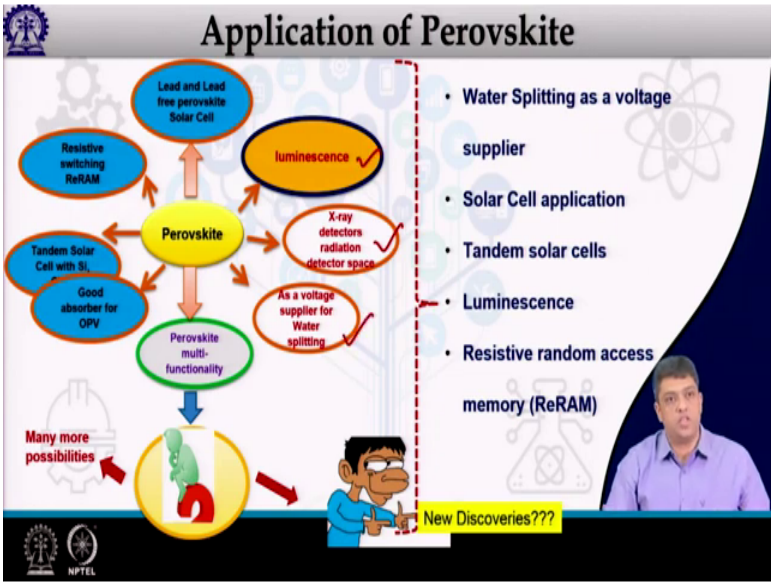

Application of Perovskite

- Water Splitting as a voltage supplier
- Solar Cell application
- Tandem solar cells
- Luminescence
- Resistive random access memory (ReRAM)

These solar cells have large scale applications. They are already being proposed for application in x-ray detectors, in devices where luminescence is occurring or places where you want to initiate water splitting or you can also have resistive switching-based devices where these systems can become useful.

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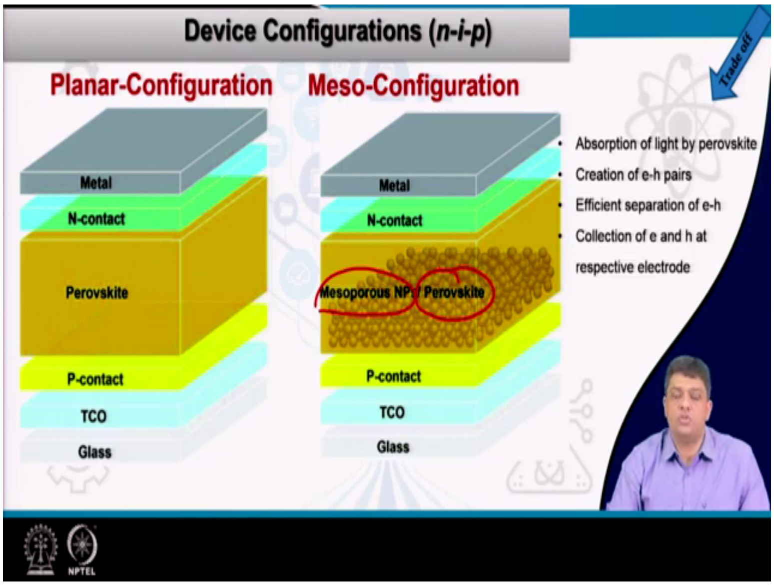

Device Configurations (*n-i-p*)

- Absorption of light by perovskite
- Creation of e-h pairs
- Efficient separation of e-h
- Collection of e and h at respective electrode

And just like silicon based solar cells, these cells can also be fabricated in various configurations. These include planar configurations or Meso configurations, these Meso configurations they use Mesoporous nanoparticles in combination with perovskite-based materials to perform the photon induced generation of charges.

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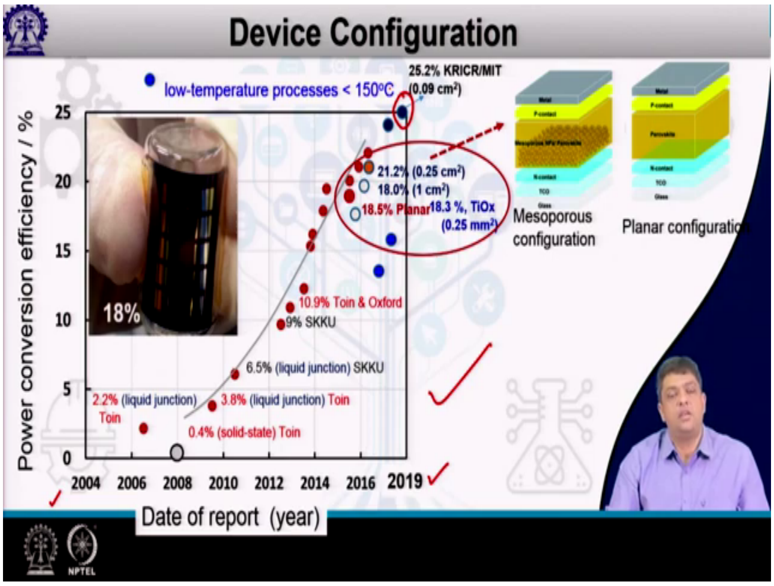

Device Configuration

And if you see the literature, if you see the literature, then let us say from 2004 to 2019, you have seen a steady growth in the efficiencies which you have obtained and as of 2019, we are talking about an efficiency of 25 percent. And you can see that the earlier technologies, they could reach these values of efficiencies after a research of more than 100 years or so, whereas perovskite-based research when it has really taken off, it could reach these values in few decades or so, and that is why these are being considered as the future of solar technologies.

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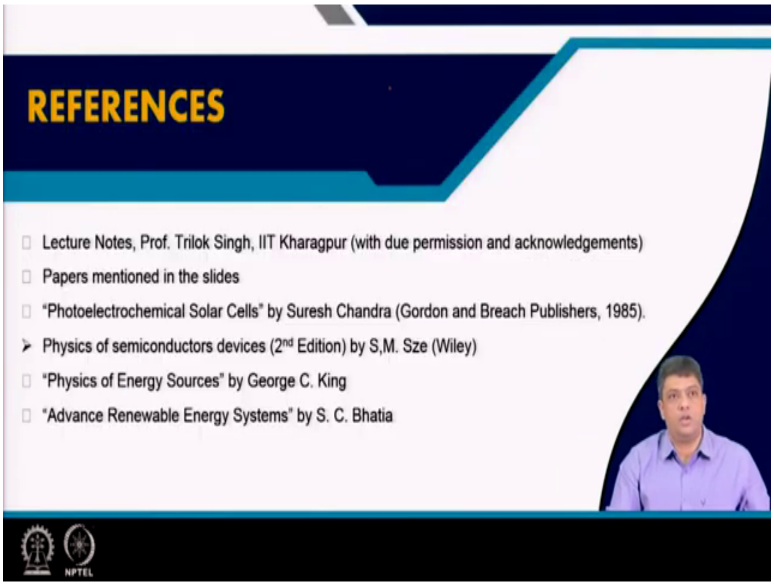

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- ☐ Lecture Notes, Prof. Trilok Singh, IIT Kharagpur (with due permission and acknowledgements)
- ☐ Papers mentioned in the slides
- ☐ "Photoelectrochemical Solar Cells" by Suresh Chandra (Gordon and Breach Publishers, 1985).
- ➢ Physics of semiconductors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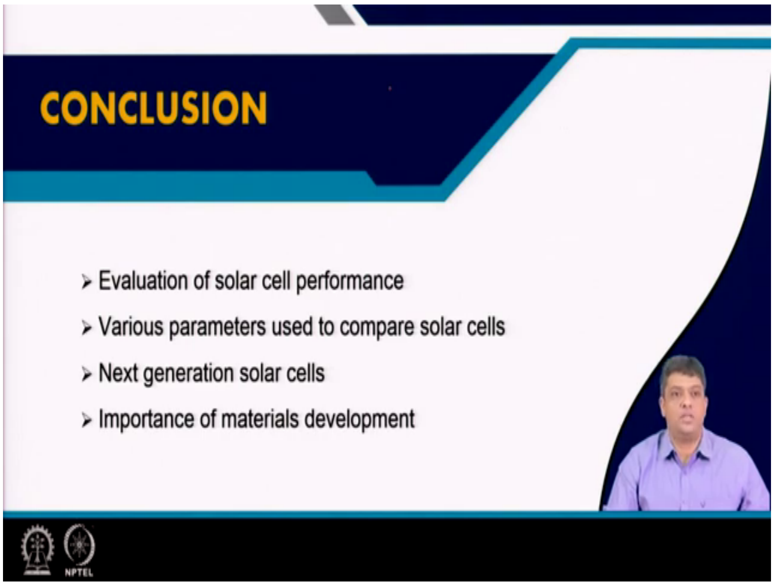

CONCLUSION

- Evaluation of solar cell performance
- Various parameters used to compare solar cells
- Next generation solar cells
- Importance of materials development

These are the references which were used to obtain the data, which were presented in today's lecture. And I hope that you have understood the process of evaluation of a solar cell, what are the parameters that are used to compare the solar cell performance. And also, what is the importance of materials development in obtaining next generation solar cells.

I thank you for attending today's lecture and from next lecture onwards, we will move towards other kind of solar based devices. Thank you very much.