Solar Photovoltaics: Principles, Technologies and Materials

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Lecture - 27
Solar PV Technologies: Introduction

Welcome again to a new lecture of Solar Photovoltaics: Principles, Technologies and Materials. So, from today we will start discussing the; from this lecture obviously, will start discussing the technologies that are that are present in solar cell landscape. So, we will just have a little recap of the last lecture.

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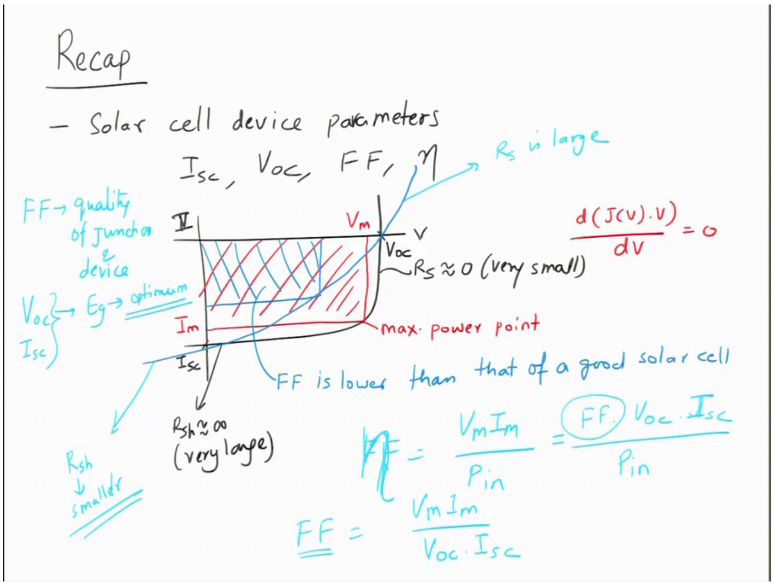
Recap

- Solar cell device parameters

I_{sc}, V_{oc}, FF, η

$$\frac{d(J(V)\cdot V)}{dV} = 0$$

$$\eta = \frac{V_m I_m}{P_{in}} = \frac{\boxed{FF}\, V_{oc}\cdot I_{sc}}{P_{in}}$$

$$FF = \frac{V_m I_m}{V_{oc}\cdot I_{sc}}$$

So, the recap of the last lecture is that we learnt about solar cell device parameters. So, we saw what is short circuit current, what is open circuit voltage, what is fill factor, and what is efficiency.

And we also saw that a typical I-V curve of a solar cell device is like this, it is in the fourth quadrant. So, the current at 0 voltage is short circuit current, the voltage at which current is 0 is open circuit voltage. And the and within this curve the there is a rectangle that you can draw which corresponds to maximum power point. And this basically comes from d of J V into V, so wherever this is equal to 0 that is the maximum power point. Corresponding to this maximum power point you have I m which is the maximum current that can be extracted and V m the maximum voltage that can be extracted.

So, this is the maximum power that you can draw out of a solar cell, which is within the I-V curve experimental I-V curve. So, the idea of a engineering materials and device engineering is that you your aim is to make this curve as square or as rectangular as possible which means, which means that series and shunt resistance must be optimised. If you have a bad solar cell a bad solar cell would appear like this. So, if you look if you now want to draw the MPP in this, the MPP would correspond to something like this.

So, for a bad solar cell the fill factor is lower than that of a good solar cell, right. You can see that the fill factor of this rectangle, is the area of this red rectangle is bigger than the area of smaller rectangle, and this is for the same V oc and I sc approximately. And this is manifested in fill factor.

So, you can see that for the black curve the series resistance is; so for the black one the and colour now. For the black one the series resistance is nearly equal to 0, whereas the shunt resistance is nearly equal to infinity. So, basically very large ok. And this is very small. And for the blue one you can see that, the series resistance is R s is large and for this R sh is smaller. And this is what results in.

So, fill factor is basically as we said is given as V m I m divided by P in, this is the incident power and this is the incident you can write in terms of energy or power. So, let us say this is V m V m I m which is the incident which is extracted energy out of a solar cell and this is a incident energy. So, if V m I m goes down.

Student: (Refer Time: 04:12) efficiency.

Sorry.

Student: Efficiency.

Sorry, this is efficiency yeah sorry. And this is equal to fill factor into V oc into I sc right; P in yes your right this should be efficiency. So, the ratio of V m I m to the incident power gives you the efficiency and this is related to fill factor. So, V m I m is equal to fill factor into V oc into I sc. So, fill factor is higher your efficiency of power extraction is going to be a power conversion is going to be better, which is where you write fill factor as V m I m divided by V oc into I sc,.

So, idea. So, there are. So, you can see from these expressions you want to maximize V m I m which is by maximizing V oc fill factor, but you also would like to maximize V oc and J sc, I sc. So, for a device engineering perspective fill factor depends upon the quality of device; quality of junction and device. Basically the job is to minimise the parasitic resistance is. V oc as we saw last time depends upon the bandgap. So, your larger the bandgap is larger the V oc is going to be, but if you increase the V oc your current also drop a even you increase the bandgap the current drops.

So, both I sc and V oc it will some extend that determined by E g and is optimum E g that you need to use. So, but it depends upon the materials which are available to you. So, typically we will see that the range varies from anywhere from 1 electron volt to 1.7-1.8 electron volt. And within this we get whatever V oc and J sc we have. And, but V oc and J sc are also dependent upon the recombination and the devices. So, if your device is bad, if a material quality is bad and even though material has promised to give you higher V oc and J sc you will end up with the lower V oc and J sc because the material quality is bad.

So, all of these factors are quite intertwined with each other, they are interrelated to each other. And many of the time for a given material they are dependent upon the kind of quality that you get after the thin film or device fabrication process.

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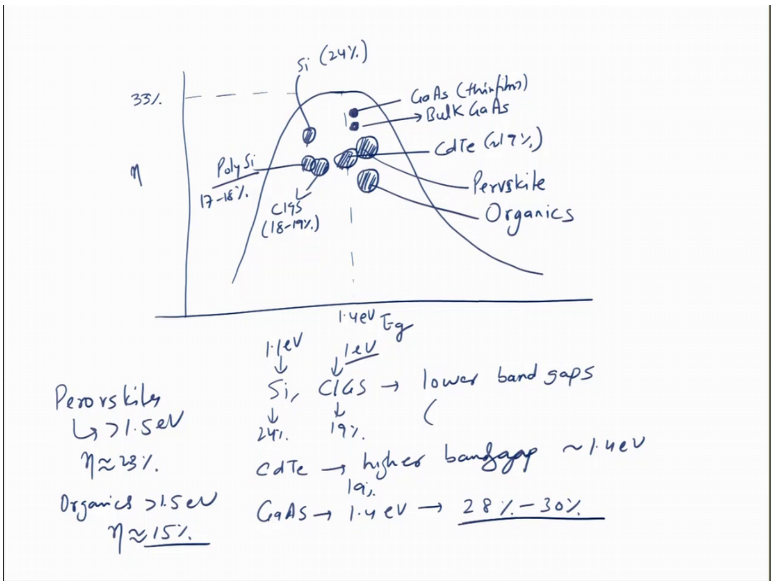

1.1eV 1eV

Si, CIGS → lower band gaps

24% 19%

CdTe → higher bandgap ~1.4eV

19%

GaAs → 1.4 eV → 28%-30%

Perovskites

↳ >1.5eV

η ≈ 23%

Organics >1.5eV

η ≈ 15%

Next I would just again draw the curve between the as we saw last time. So, the this is the efficiency curve with as a function of E g. And this curve goes something like this. And this maximum efficiency is about 33 percent, and this falls around the bandgap of nearly 1.4 E v.

So, we have somewhere here about 30 we have gallium arsenide, so this is gallium arsenide. So, this is thin film gallium arsenide, this is bulk gallium arsenide, silicon is somewhere here its bandgap is 1.1, so this is silicon. This is at about 24 percent or 24.7 percent. Polysilicon is lower, this is polysilicon which is it about 17-18 percent. Then we have CIGS which is C I G S, Which is again at about 18-19 percent. And then we have CdTe also somewhere here, which is about 19 percent or so. These are approximate numbers. And then we have perovskite which has already approached 20 percent. So, perovskite would be somewhere here perovskite. Organics are lower around 13-14 percent, although there are reports of 15 percent nowadays. So, you can you can see that these are different materials that you have it in different domains.

So, bandgaps are centred around 1.5 electron volt; some materials have bandgaps higher than 1.5 electron volt, some materials have. So, materials like silicon, CIGS they have lower bandgap ok. And their efficiency is of the order of; so silicon is crystalline silicon is about 24 percent, CIGS is about 19 percent, CdTe bandgap is larger so around 1.4 E V, this is silicon is about 1.1 E V, this is about 1 E V or so. It depends upon the composition. CdTe again gives you about 19 percent; gallium arsenide is 1.4 or so. This gives you about nearly 28 percent or so; 28 to 30 percent roughly and crystalline. So, you have various numbers for gallium, arsenide, perovskites have a bandgap which is higher than. So, higher bandgap so greater than 1.5 E V and they give you eta today as of today about 23 percent.

These are efficiency if the cell level, not at the module level ok. For laboratory skill efficiency is organics give you more than 1.5 E V again, they give you efficiency of the order of 15 percent or so. And on top of these we have tandem cells where we can mix and match the bandgaps as I said last time we can stack them together, they give you higher efficiencies. But in this course mostly we will be talking about the single junction devices not the multifunction devices.

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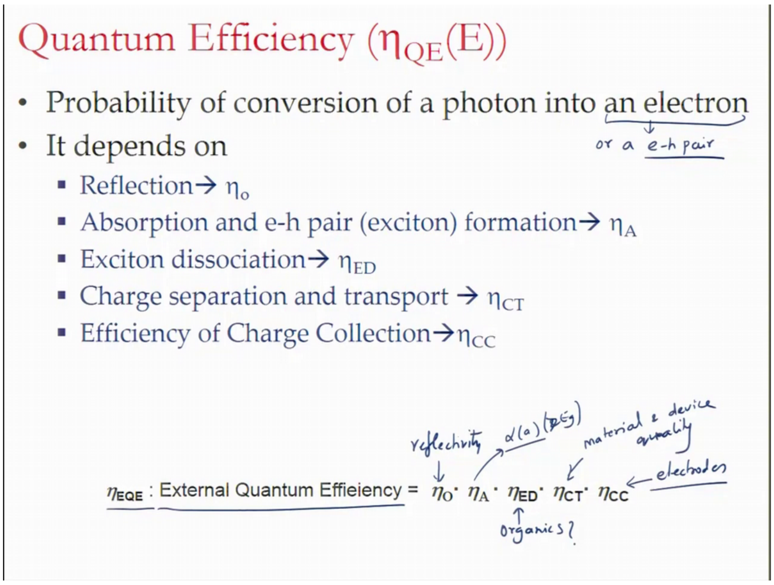

Quantum Efficiency ($\eta_{QE}(E)$)

- Probability of conversion of a photon into $\underbrace{\text{an electron}}_{\text{or a } \underline{\text{e-h pair}}}$
- It depends on
  - Reflection→ η_o
  - Absorption and e-h pair (exciton) formation→ η_A
  - Exciton dissociation→ η_{ED}
  - Charge separation and transport → η_{CT}
  - Efficiency of Charge Collection→η_{CC}

$$\underline{\eta_{EQE}} : \underline{\text{External Quantum Effieiency}} = \overset{\text{reflectivity}}{\eta_O} \cdot \overset{\alpha(a)\,(E_g)}{\eta_A} \cdot \underset{\text{organics?}}{\eta_{ED}} \cdot \overset{\text{material \& device quality}}{\eta_{CT}} \cdot \eta_{CC} \leftarrow \underline{\text{electrodes}}$$

So, there is in the in the solar cell literary jargon they cannot come that will come into consideration is called as quantum efficiency. Quantum efficiency is essentially the probability of conversion of a photon into electron hole; an electron or you can say a electron hole pair or a e-h pair which eventually get separated and gives you a electron and a hole.

So, it depends upon various factors. So, the first factor it depends upon is reflection and efficiency of reflection is depicted as eta O. It also depends upon absorption and electron pair or exciton formation; efficiency of that is eta A that is absorption and formation ok. Exciton dissociation ones the exiton forms it has to dissociate. And there is exciton dissociation efficiency corresponding that at this eta E d. And then charge separation and transport that is eta CT. And then efficiency of charge collection at the electrodes which is eta CC. So, the net external quantum efficiency is a product of all these efficiencies. The optical efficiency the reflection one, the absorption and exciton formation efficiency that is eta A, exciton dissociation efficiency which is eta E d, charge separation and transport which is eta CT, and eta CC is a charge collection. So, you can see each of these factor is a independent factor determined by various factors.

So, eta O is going to be determined by the reflectivity of the stop surface ok. And that is why in the solar cells we use nowadays antireflection coatings specially for silicon and other kind of solar cells not so much for organics and perovskites. So, basically you would like to minimise the reflection losses, which means you would like to reach make this eta O closed to 1. Then we have eta A which is absorption.

So, basically above the bandgap all the energies must be absorbed. So, you want to maximize this absorption efficiency, so this is related to alpha a and the bandgap. And then we have; so above the bandgap basically you would like to absorb everything. Then we have exciton dissociation, this is usually not a problem in case of in organic semiconductors it could be an issue in organic semiconductors. So, this is a problem in organics, otherwise its alright you get pretty high exciton dissociation efficiency in a in organic semiconductors.

Absorption efficiency of course is higher for direct bandgap semiconductors than for indirect bandgap semiconductor. And then we have charge transport. Charge transport depends upon the type of semiconductor you have, what is the series resistance you have, I do you have any losses within the during the transport. So, that will be determined by material and device quality.

The parasitic resistances and so on and so forth and then you have efficiency of charge collection, what kind of electrodes you have on the surface, what kind of are there any trap should the electrode interface; whether they have the right work function to extract the charges. So, this is this is determined by the electrodes. So, you can see that your device design will require to optimise all of these you would like to minimum minimize reflection, you would like to maximize the absorption, you would like to maximize the efficiency of exciton dissociation which is normally not a problem, but you must have some built in field built in force to break the exciton and dissociate into electron hole pairs especially in organics.

Then we have charge transport, which is you need to maximize the charge transport efficiency. So, the charges and all not lost on emperor on the way which is determined by material and device quality. And then we have electrodes which come into picture because the kind of energy levels, the kind of conductivity of electrodes, the kind of interfaces they make with the solar cells is very important in charge collection. So, all of these together will give you a external quantum efficiency which is called as eta E q E. And this can be experimentally measured and this can be directly correlated to the current ok.

So, ideally the current that you obtain should a scale with the external quantum efficiency, right.

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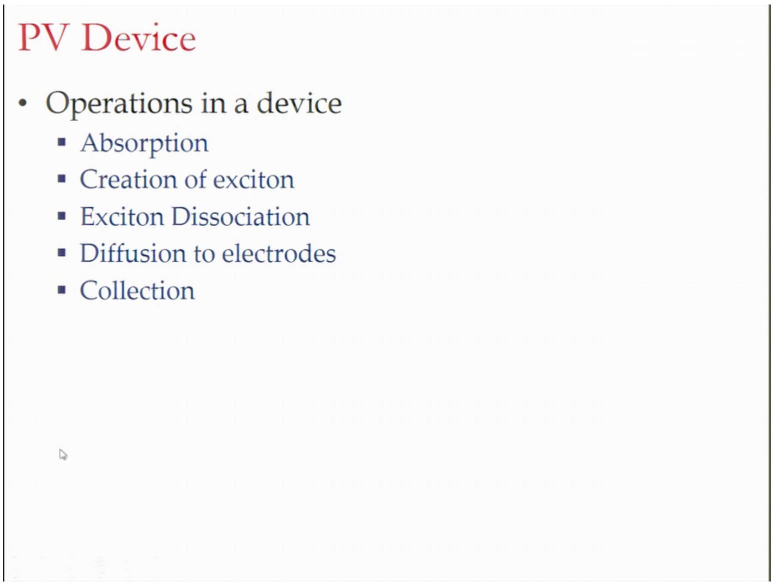

PV Device

- Operations in a device
    - Absorption
    - Creation of exciton
    - Exciton Dissociation
    - Diffusion to electrodes
    - Collection

So, if you look at a PV device based on this efficiency there are of the operations are fairly straight forward. So, the operations in a PV device is first you have light absorption, then you have creation of exciton, then you have exciton dissociation, then you have diffusion to the electrodes, and then you have charge collection. And this is what the and just we as we saw the external quantum efficiency is made up of.

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So for example; if you look for a given device let us say we have photon flux density as a function of wavelength. So, photon flux density goes as a something like you know; goes as something like that right and it goes to higher wavelengths. So, this is your photon and these are absorption bands at different wavelengths. And so the quantum efficiency, let us say you have a solar cell whose bandgap is somewhere here.

So, if you if this is a solar spectrum that is reaching the solar cell the quantum efficiency 100 percent would mean that you will absorb everything, you will not lose everything and as far as a solar cell permits, right; it do not absorb anything below the bandgap. So, starting from here up to the bandgap it will absorb everything. So, this would mean that your quantum efficiency is equal to 100 percent, because you have absorbed everything that was available to you. And which is lead to formation of electron and hole pair.

So, essentially 100 percent QE would mean that 100 percent conversion of photons into electron hole pairs which get collected. So, these are there are no losses right. So, there are no losses. That is the objective we have. And this depends upon various factors as we just showed.

So, now, let us look at the more practical aspects of solar cell devices; that is the evolution of solar PV first before we go to gen I. So, evolution of solar PV has happened through stages.

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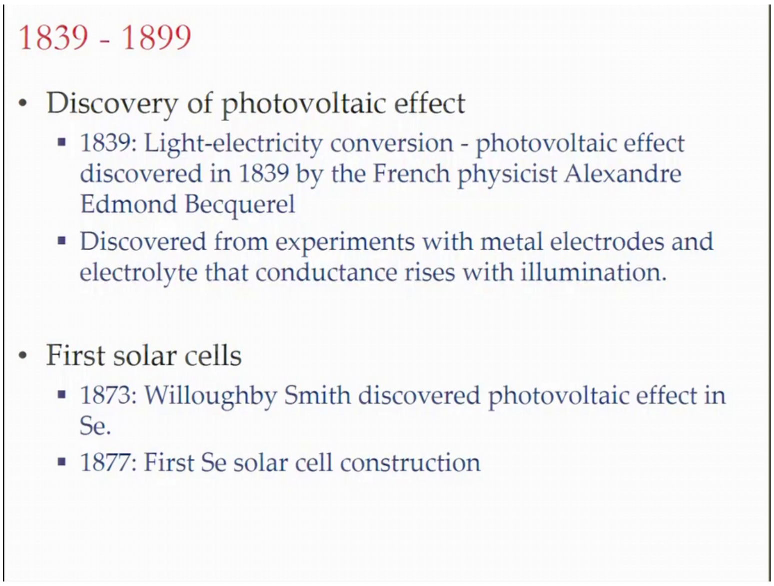

1839 - 1899

- Discovery of photovoltaic effect
  - 1839: Light-electricity conversion - photovoltaic effect discovered in 1839 by the French physicist Alexandre Edmond Becquerel
  - Discovered from experiments with metal electrodes and electrolyte that conductance rises with illumination.
- First solar cells
  - 1873: Willoughby Smith discovered photovoltaic effect in Se.
  - 1877: First Se solar cell construction

So, 1839 was the time when Becquerel discovered this light electricity conversion, which was called as photovoltaic effect, he was a French physicist. And this was determined from experiment using metal electrodes and using electrolyte whose conductance changes with the illumination.

So, this was in 1839. The first solar cells however made in 1873, when photovoltaic effect was discovered in selenium. And then 1877 was a time when first selenium solar cell was made.

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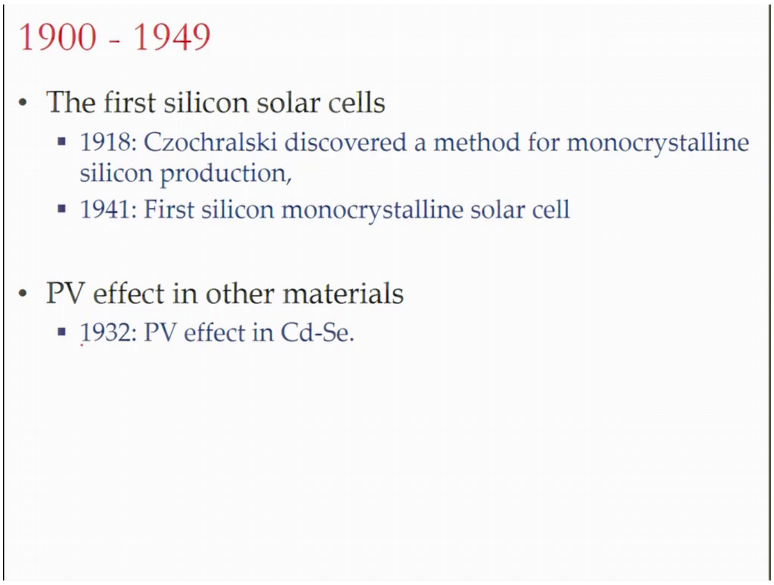

1900 - 1949

- The first silicon solar cells
  - 1918: Czochralski discovered a method for monocrystalline silicon production,
  - 1941: First silicon monocrystalline solar cell
- PV effect in other materials
  - 1932: PV effect in Cd-Se.

Of course, there are lot of other intermediate stages which I am not going which we do not have time to get into. But and then came the age of silicon. So, 1918 first after the First World War we have Czochralski who discovered a method for making monocrystalline silicon. However, the first silicon monocrystalline solar cell came in 1941. And then in between in 1932 you people also observed PV effect in cadmium selenide.

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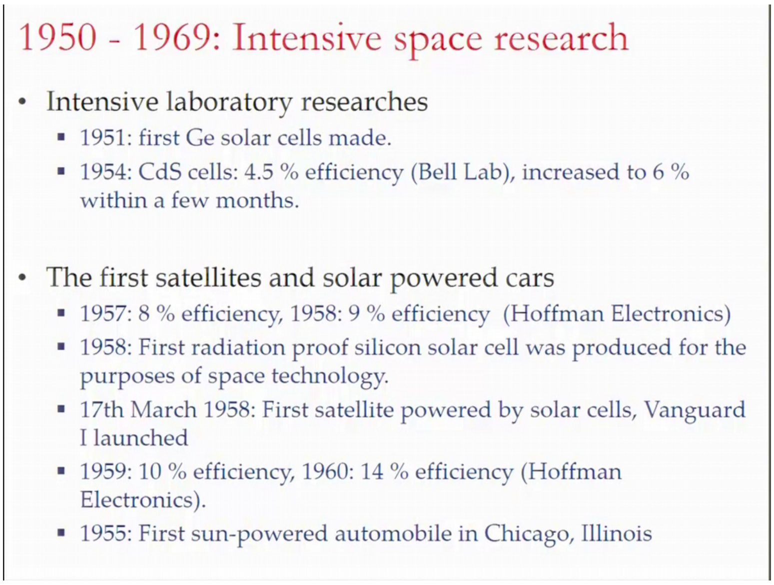

1950 - 1969: Intensive space research

- Intensive laboratory researches
  - 1951: first Ge solar cells made.
  - 1954: CdS cells: 4.5 % efficiency (Bell Lab), increased to 6 % within a few months.
- The first satellites and solar powered cars
  - 1957: 8 % efficiency, 1958: 9 % efficiency (Hoffman Electronics)
  - 1958: First radiation proof silicon solar cell was produced for the purposes of space technology.
  - 17th March 1958: First satellite powered by solar cells, Vanguard I launched
  - 1959: 10 % efficiency, 1960: 14 % efficiency (Hoffman Electronics).
  - 1955: First sun-powered automobile in Chicago, Illinois

And then we have 50s to 60s when intensive space research was conducted primarily on solar. So, because that the problem with space was you if you wanted to sell satellite you needed you need them to be powered up, right. And you could not there is no way you can send cables from earth to space.

So, what was the source of electricity? The photovoltaic was the source of electricity. So photovoltaics, benefited from satellite di space programmes of us and Russia and those times. And cost was not a factor. So, as a result intensive effort was made to develop solar cells of high efficiency; high efficiency because you wanted to reduce the rate of satellite. If you had lower efficiency solar cells which means you need to put in more solar cells which will increase the weight of the satellite. So, there was lot of effort on making high efficiency solar cell so that satellite could remain powered up in the space.

So, 1951 the first germanium solar cells were made. 1954 cadmium sulphide solar cells were made with 4.5 percent efficiency which was increased to 6 percent in a in a in a few months. And then in 1957 we had solar powered cars. And 1950s we have solar powered cars and satellites. So, 1958 was the time when first radiation proof. So, as radiation is a problem in space as a result radiation proof silicon solar cell was needed it was made in 1958.

Then march 1958 the first satellite powered by solar cells hat is vanguard one was launched in the United States. In the 1959 and 60s let us phenomenal increase in the efficiency of silicon solar cells in went up to 14 percent. 1955 was a time when we had first sun powered automobile in Chicago.

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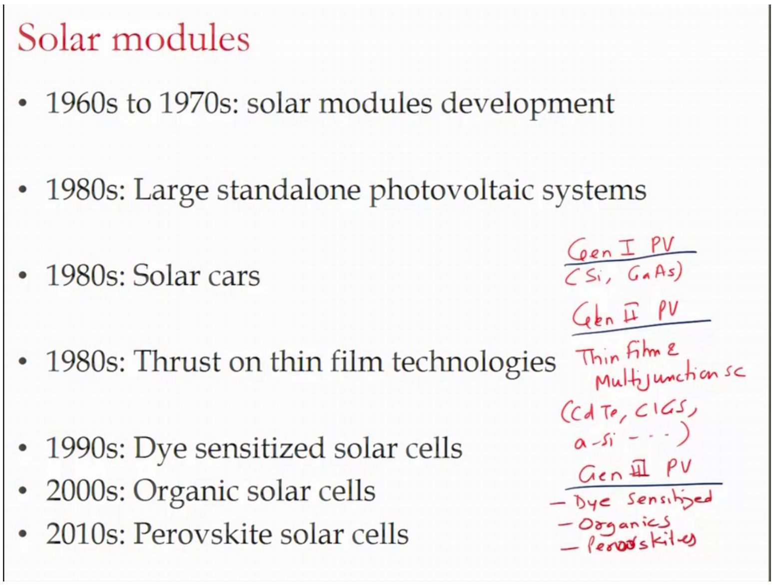

Solar modules

- 1960s to 1970s: solar modules development
- 1980s: Large standalone photovoltaic systems
- 1980s: Solar cars
- 1980s: Thrust on thin film technologies
- 1990s: Dye sensitized solar cells
- 2000s: Organic solar cells
- 2010s: Perovskite solar cells

Gen I PV
(Si, GaAs)

Gen II PV
Thin film &
Multijunction sc
(CdTe, CIGS,
a-Si - - -)

Gen III PV
- Dye Sensitized
- Organics
- Perovskites

And this paved the way for solar module development that is large scale solar power development 60s and 70s. There was a massive effort on developing solar modules. 1980s lot of large stand-alone systems were developed not necessarily grid connected for commercial purposes. It is the effort on solar cars and also.

And then 80s we started research on thin film technologies. And these were important because silicon solar cells were heavy, because they use vapour of silicon. So, the idea was to reduce the weight of the solar cell and reduce the material cost also by using materials in thin film form. So, there was a lot of effort on developing technology is which was thin film technology is such as the cadmium telluride CIGS amorphous silicon and so on and so forth.

And then with the discovery of new materials 1990s (Refer Time: 21:28) discovered the dye sensitized that is electrochemical solar cell. 2000s lot of research was done on organic solar cells which is based on polymer and plastics based materials. And in 2010 we have intensive research on perovskite solar cells. And somewhere in between we also have multi junction solar cells with multi junction solar cells the work is started quite early, because I have ability to match the bandgaps and people saw potential increase in the efficiency although they are expensive.

So, this is sort of a chronological development of solar cells over the years, and because of this the solar cells are often characterized in three categories. First is the gen I PV; gen I PV is primarily based on silicon and gallium arsenide which is started in 19 60s or 50s. So, then we have gen II PV, this is basically on thin film and multi junction solar cells. And this is primarily based on cadmium telluride, copper indium gallium selenide-CIGS as we call it, amorphous silicon, and so on and so forth. And so this is gen I, this is gen II, and then we had if I now draw a line here and then we have gen III; which means dye sensitized, organics, and perovskites.

So, these are the three categories of solar cells which have been which in which we can divide the journey of solar photovoltaics ok. And this is how we will go, we will first look at some of the aspects of gen I solar cells and material issues, technology issues, design issues. Then we will move on to gen II PV which is mainly thin film silicon, thin film solar cells and multi junction solar cell. And finally, we will look at the issues and materials related to the dye sensitized, perovskites and organic solar cells ok.

So, this is the order in which we will go now in this course.

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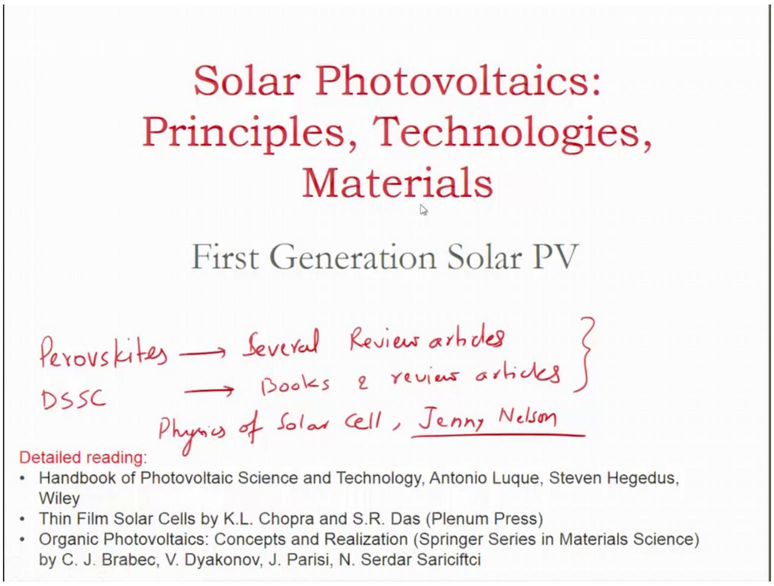

Solar Photovoltaics: Principles, Technologies, Materials

First Generation Solar PV

Perovskites → Several Review articles
DSSC → Books & review articles
Physics of Solar Cell, Jenny Nelson

Detailed reading:
- Handbook of Photovoltaic Science and Technology, Antonio Luque, Steven Hegedus, Wiley
- Thin Film Solar Cells by K.L. Chopra and S.R. Das (Plenum Press)
- Organic Photovoltaics: Concepts and Realization (Springer Series in Materials Science) by C. J. Brabec, V. Dyakonov, J. Parisi, N. Serdar Sariciftci

If you want to go through books I would suggest this: for silicon and thin film technologies at least gen I and gen II this handbook is very good, this is Handbook of Photovoltaic Science and Technology by Antonio Luque and Steven Hegedus from Wiley, excellent book for gen I and gen II. Again we have another book nice book by

K.L. Chopra and S.R. Das-Thin Film Solar Cells. For organic and perovskites there are not many books available, but for organic photovoltaics you can read you can go through this book on Organic Photovoltaics Concepts and Realization by Brabec, Dyakonov Parisi, N. Sariciftci.

For perovskites there are several review articles in journals, ok. And similarly for DSSC that is dye sensitized solar cells there are books written books as well as review articles. However, for all of them you will also find a lot of review articles very nice review articles written on each of the technology solar cell technology. And of course, you can look at this book Physics of Solar cells by Jenny Nelson it does not talk so much about the manufacturing, it is mostly about the science of solar cells, alright.

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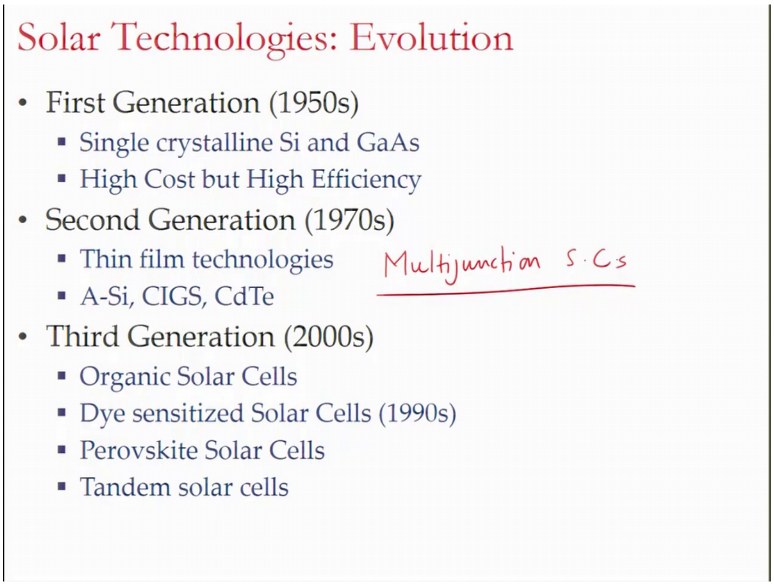

Solar Technologies: Evolution

- First Generation (1950s)
  - Single crystalline Si and GaAs
  - High Cost but High Efficiency
- Second Generation (1970s)
  - Thin film technologies
  - A-Si, CIGS, CdTe
- Third Generation (2000s)
  - Organic Solar Cells
  - Dye sensitized Solar Cells (1990s)
  - Perovskite Solar Cells
  - Tandem solar cells

Multijunction S.Cs

So, I said first generation technologies are 19 1950s, there the work started. So, there were primarily based on single crystalline silicon and gallium arsenide and also the work started on multi crystalline silicon during this time. They are of high cost, but high efficiency ok. And this is a high efficiency was a reason why lot of efforts we made to on the technologies, because they could reduce the weight of satellites and weight of panels in general for other applications as well.

Then the second generation work started in 70s and 80s. So, we have thin film technologies mainly, and this could be amorphous silicon primarily amorphous silicon CIGS and CdTe, but also multi junction solar cells. And third generation 2000s we have worked on organic solar cells; dye sensitized solar cells were work started in 1990s although. Perovskites solar cells and we also have tandem solar cells. Multi junction will also fit in this category, and the work on multi junction started actually quite early ok; multi junction tandem solar cells.

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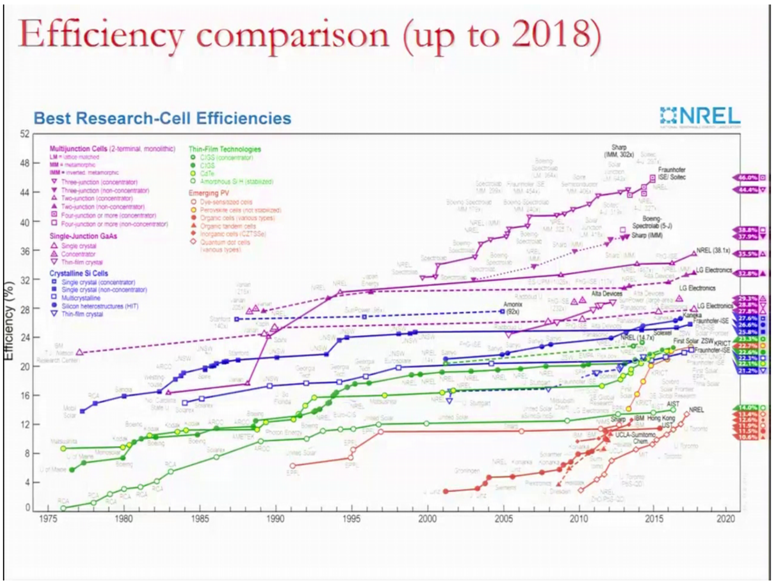

Efficiency comparison (up to 2018)

And this is a famous efficiency plot from NREL which publishes this in the public domain. And this diagram is referred by most of the researchers out in the world. And you can see that if we if I go for first the crystalline silicon, crystalline silicon is in the blue lines and the non-concentrated technology silicon is about 25.8 percent as of 2000. So, this one on the right here.

So, this is this is the one which is this one 25.8. And if you use the concentrated technology the which uses a concentrator concentrated sun light the efficiency is about 27.6 percent which means you the intensity is not a m 1.5 it is higher than a m 1.5. And if you go to thin film technologies the one ones in the green the CIGS has a number of about 23 percent right now laboratory scale. So, its, but it is in the concentrator mode. If you go to non-concentrator mode the efficiency is about 22.6 percent which is here, this is non concentrator. And cadmium telluride is about 22.1 percent. These are laboratory best efficiencies these are the average efficiencies.

So, these are the world records in that in that sense. And there amorphous silicon lies low at 14 percent and the work on amorphous silicon is almost stopped now. And the emerging PV is the one which is the third gen technologies. And that is where we have proverskite leading the chart and at 22.7, right now its more than 23 percent as these peak today the world record. And then we have organics and SP it the one this is quantum dot at 13.4. Then we have inorganic CZT which is copper zinc lead in selenite which is again a new PV technology about 12.6 percent a very promising one. Then we have organics in the and the red dots which is at 11.5, right now it is about 13-14 percent the world record.

So, there are various technologies, and you can see on top of the chat we have this multi junction technologies which include more than 1 material ok. So, for example, the on the right on the top we have this four-junction technology which is at about 46 percent. But these are very expensive technologies and very difficult to make. So, they are primarily for a demonstration purposes or solar or space technology programs or for some (Refer Time: 29:19) applications. And mostly the research on these is led by industries, you can see that and the research is mostly industrial centres or groups led.

Then we have 44.4 percent which is in triple junction concentrator, so this is for triple junction. And then we have various other concentrated technologies as you can see on the left here. We can see here in the summary the concentrated technology leads the efficiency chat right now, which in the multi junction technology which is more than one junction. And then we have silicone perovskite. And then we have thin film PVs. And then we have lot of emerging PVs

So, future is quite bright as for as solar energy is concerned. And given that recently we have had cost reductions in silicon photovoltaics future is certainly quite bright.

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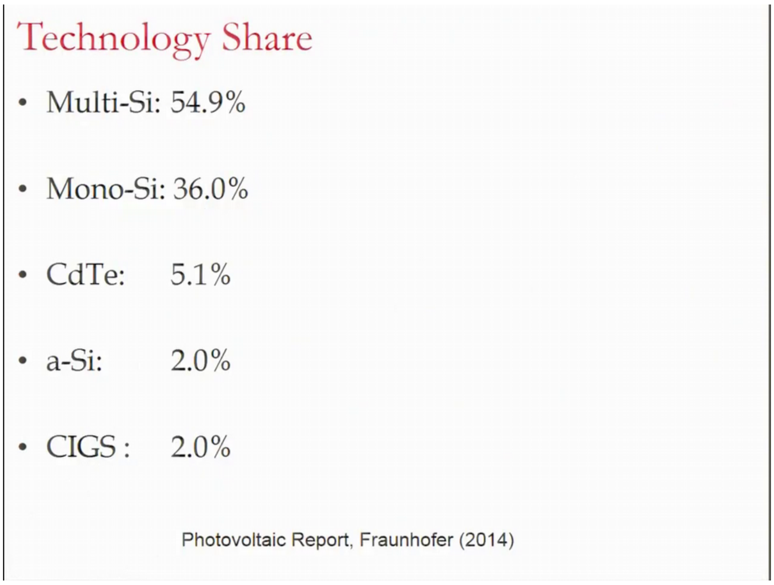

Technology Share

- Multi-Si: 54.9%
- Mono-Si: 36.0%
- CdTe: 5.1%
- a-Si: 2.0%
- CIGS : 2.0%

Photovoltaic Report, Fraunhofer (2014)

So, right now as of 2014 report the technology share multi silicon has a technology share of about 54.9 percent. And in case of silicon, silicon you can see the numbers here a multi crystalline silicon is this the blue square. And multi sili multi crystalline stands it about 22 percent, which is not bad and because considering that cost of multiple crystalline silicon is lower than single crystal silicon. So, multi crystalline leads the way because of lower cost as comparison to crystal silicon which is about 55 percent market share.

Mono-silicon which is crystalline single crystal silicon is about 36 percent, so together they have a market of nearly 90 percent. And remaining 10 percent is occupied by cadmium telluride, amorphous silicon 2 percent, CIGS 2 percent. Amorphous silicon is now pretty much a close technology is just there are not too many investments coming up in this technology. And it is expected that cadmium telluride and CIGS will share will rise as a function of time. It is also possible in the future perovskite and some other technologies start entering the market. Perovskite and other technologies are still on research state there have not been commercialized, but it is likely because the lifetimes are in issue. But once the lifetime issues are solved there is a possibility that they might enter into the market.

So, what are the key issue of one of the key attribute of a solar cell technology is that sends solar cell technology is not a is not very cheap technology as of now, the lifetime is a major issue. So, one would expect a solar panel which is installed in a solar form in your house to at least last for 20 years. So, is 20 year requirement that is a very stringent requirement on the new technologies and that is why most of the technologies are not able to beat in organic solar cells when it comes to life time?

So, let us come to the principal of cell design.

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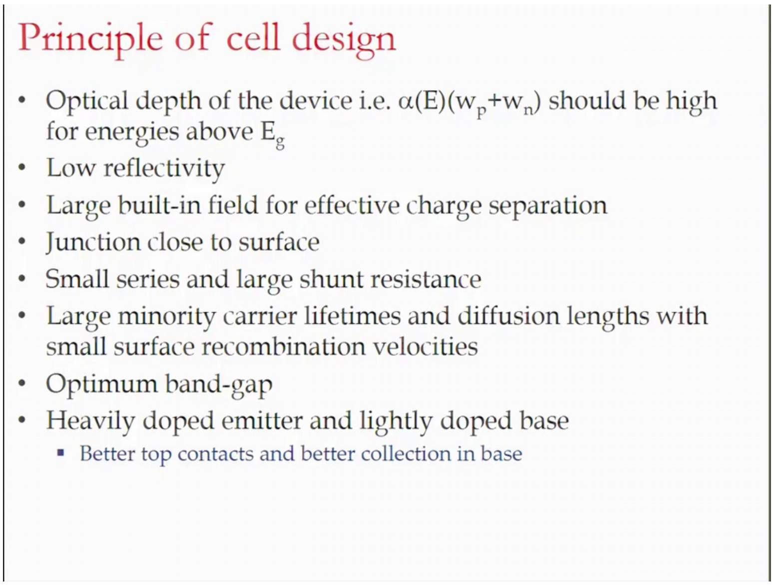

Principle of cell design

- Optical depth of the device i.e. $\alpha(E)(w_p+w_n)$ should be high for energies above E_g
- Low reflectivity
- Large built-in field for effective charge separation
- Junction close to surface
- Small series and large shunt resistance
- Large minority carrier lifetimes and diffusion lengths with small surface recombination velocities
- Optimum band-gap
- Heavily doped emitter and lightly doped base
  - Better top contacts and better collection in base

So, how do you design the cell in a in a given in a solar cell. So, the first thing is as we said from the quantum efficiency perspective. The optical depth of the device that is alpha E absorption coefficient into W p plus W n which is the width of depletion region total should be high for energies above E g. So, which means the optical depth the depth in which solar cell absorbs the device absorbs light that should be good enough so that you are able to absorb all the energies above E g.

The device must have low reflectivity. It must have large built in field for effective charge separation. The junction should be close to the surface so that you have. So, we will come to the we will come to the reasons for this the specially in case of silicon it is very important the junction should be close to the surface, and this is mainly because of recombination in the different types of materials.

The device must have small series and large shunt resistance as we have seen. The minority carriers must have long life times and diffusion lengths with a small surface recombination velocities. The material must have optimum bandgap. And generally we prefer specially for silicon a heavily doped emitter that is on top and a lightly doped base. And this is mainly to ensure you have good contacts and better collection in especially in the base region.

So, we will come to the details of these from the perspective of silicon in the next lecture, because we are running out of time for this lecture. And so, what we have discussed is basically the evolution of solar cells, and general framework in which we will now discuss the rest of the lectures.

Thank you.