Solar Photovoltaics: Fundamental Technology and Applications
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Lecture - 35
Tandem Solar Cells

Welcome everyone to our solar photovoltaics course. This week, we are having our 7th week lecture and today is our last module of the 7th week. Now, you have all known that for a single junction silicon solar cell or for that say any single junction solar cell, the maximum efficiency we can achieve is 32% and this limit comes from the thermodynamics limit called the Shockley-Queisser limit.

Now the absurd above this is that even if somebody made a very high efficiency or very high absorbing light absorbing material and let us say I optimize the morphology in the best possible way so that the charge transport and also the charge recombination is optimized to get a maximum efficiency but still there is some limitation which comes intrinsically from the devices because of that we cannot go beyond a particular number.

Now, people are thinking how to circumvent this, how to make a solar cell with more efficiency. Let us say for example like if you wanted to have some practical applications or if you need a larger power output, then somewhat like 15% or 20% whatever we get from a single junction solar cell is not sufficient. So, in that case, what we can do, we can stack many solar cells together.

Now, whenever we say that we can stack many solar cells together then we can either stack similar kind of solar cell like we can stack perovskite solar cell or we can stack silicon and perovskite together. Now, this kind of configuration is called a tandem solar cell. In today's lecture, we will discuss about the tandem solar cell.

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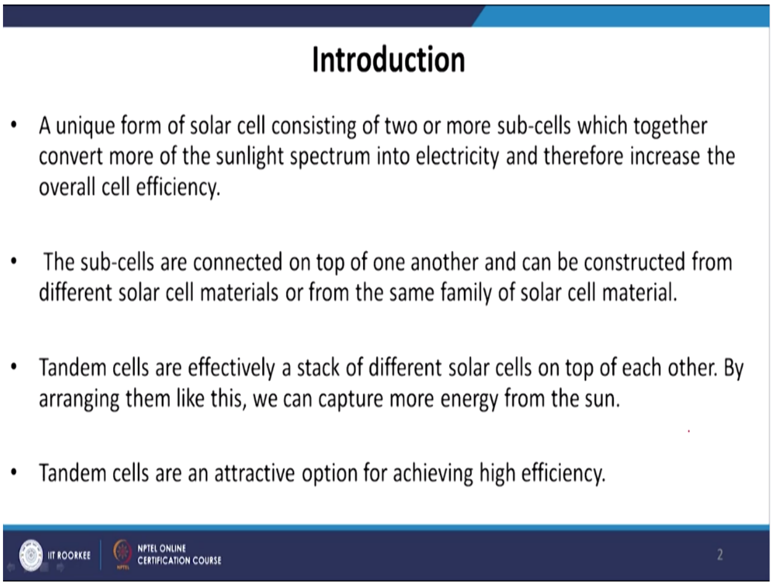

So, this is a very unique form of solar cell consisting of two or more sub-cells which together convert more of the sunlight spectrum into electricity and therefore increase the overall cell efficiency. So, just as we mentioned that if you have a single solar cell from an amorphous silicon solar cell let us say we get 12 to 15% efficiency and we know that from a perovskite solar cell we can get 15 to 20% efficiency.

But in some way, if we can make a stacking of a silicon and perovskite together then we can utilize the advantage of the silicon as well as the perovskite solar cell. So, this kind of geometry is will be called a tandem solar cell or silicon perovskite tandem. The sub-cells are connected on top of one another and can be constructed from different solar cell materials or from the same family of solar cell material.

Now, these two different components of the hybrid solar cell or tandem solar cell, they can be same solar cell material. For example, you can take two silicon solar cell or they can be from different family members like you can take a silicon and also you can take an organic solar cell or you can take a silicon, you can take a perovskite solar cell. Tandem cells are effectively a stack of different solar cells on top of each other.

By arranging them like this, we can capture more energy from the sun. Tandem cells are an attractive option for achieving high efficiency.

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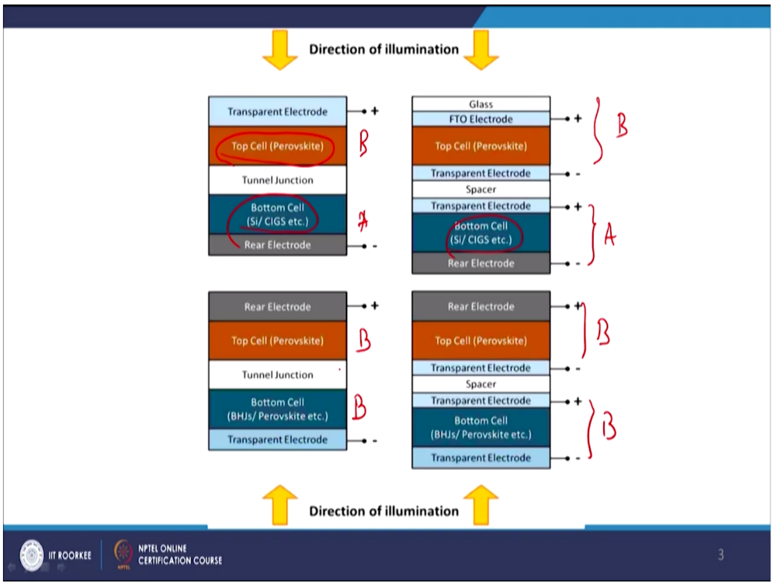

Now, look at this figure where we are showing this tandem solar cell where the direction of illumination is through the front electrode or the transparent electrode and you see that here there are two different kinds of solar cell has been sandwiched. The bottom cell is a silicon or CIGS based solar cell and then the top cell is a perovskite solar cells. Now, we put a tunnel junction in between them and it has been sandwiched between these two electrodes, rear electrode and transparent electrode.

Now, similarly we can make a bottom solar cell by a silicon CIGS based solar cell then we can put a transparent electrode. So, basically this whole unit is one solar cell and we put a spacer and put another layer of perovskite solar cell. So, basically there are two different kinds of solar cell A and B with a spacer layer that has been attached together.

And in the third case you see that here there is a perovskite solar cell at the bottom and in the top also there is a perovskite solar cell but also you can use bulk heterojunction solar cell. So, basically we can use either same type of solar cell like this one is an example of B and B. So, in the both in the bottom layer and in the top layer, we are using perovskite solar cell and in the fourth case, we have this BHJ or perovskite solar cell.

And another is also a perovskite solar cell but there is a spacer between them too. So, this is a B and this is also B but there is a spacer unit between these two and here in this case like you know this is A and this is B. So, what is the difference between this four different architecture is the following.

In one case, in the figure number 1A so whatever we are seeing here that two different kinds of solar cell like silicon or CIGS solar cell and perovskite solar cell, they have been sandwiched in a same solar cell geometry in between there is a tunnel junction. In this case, the same CIGS or the perovskite solar cell or let us first like you know take this example in the figure number 2, here the CIGS solar cell and the perovskite solar cell both are two different material solar cells.

But they are two individual solar cells which have been attached by a spacer layer. Now, also it is possible to make a tandem cell from the same materials. For example here, you see that both of this case we have a perovskite material and the number 3 and 4, the only difference is that in number 3, the both the solar cells have been sandwiched in between a tunnel junction and here this is two different solar cell made of the perovskite which have been sandwiched with each other.

So, these are the 4 different possible architectures or configuration possible for a tandem solar cell. Now, this is for a representative example. For generalization, we can take any of the solar cell configurations and we can make either silicon perovskite tandem or we can make silicon BHJ tandems. Of course, we have to look for the energetics and charge transport properties and we have to see that we get finally an optimized morphology.

Because the final objective is of making tandem solar cell is to improve the efficiency. So, while constructing this process, one thing has to be kept in the mind that the charge transport property should be optimum.

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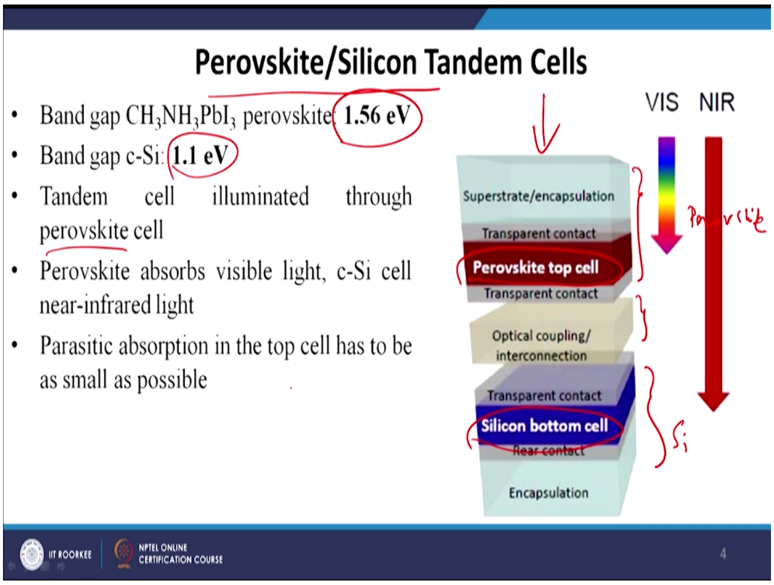

Now, a very common example of the tandem solar cell is a perovskite silicon tandem cells here. As for example, you can look at this device structure here, in the top solar cell we have a perovskite top cell and in the bottom we have a silicon bottom cell. Now, there are two different solar cells, this is a silicon solar cell right and this is a perovskite solar cell and these two solar cells has been connected by an optical coupling.

Now, how does this optical coupling has been done? This optical coupling has been done through a spacer material which allows the light to transmit completely and which couples the electromagnetic wave or the light which is coming from the like bottom solar cell or from the top solar cell towards the bottom direction. So, band gap of the CH3NH3 lead perovskite is 1.56 electron volt and band gap of the crystalline silicon is 1.1 electron volt.

So, idea is that if we make a tandem, so we can utilize the two different bandgap properties of the two different materials because like 1.56 corresponding to a particular wavelength of the absorption and 1.1 electron volt will corresponds to a particular wavelength of the absorption. For example in the figure here, we are showing here like once you use the perovskite solar cell, so the visible spectrum has been fully covered.

But when you use a silicon solar cell, not only the visible but NIR spectrum is also covered, so that means in the tandem case both the visible and the NIR spectrum is completely covered. So, tandem solar cell is illuminated through the perovskite solar cell like you know we are eliminating it through here and perovskite absorbs the visible light and crystalline silicon cell near infrared light and parasitic absorptions in the top cell has to be as small as possible.

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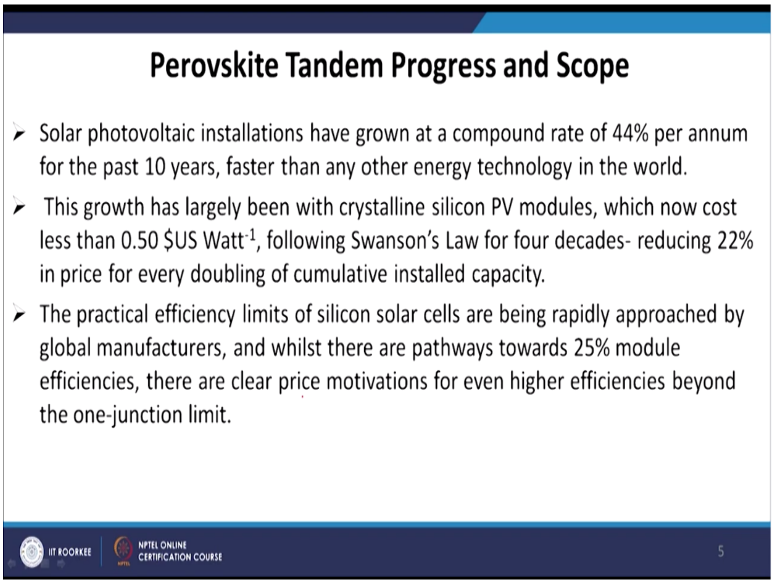

Perovskite tandem progress and scope; solar photovoltaic installations have grown at a compound rate of 44% per annum for the past 10 years, faster than any other energy technology in the world. This growth has largely been with crystalline silicon PV modules, which now cost less than 0.50 US dollar per Watt, following Swanson's Law for four decades reducing 22% in price for every doubling of the cumulative installed capacity.

The practical efficiency limits of silicon solar cell are being rapidly approached by global manufacturers, and whilst there are pathways towards 25% module efficiency, there are clear price motivations for even higher efficiency beyond the one-junction limit. So, again like in a silicon solar cell since it is kind of a mature technology, we can even go up to an efficiency of 25% in a module level.

But when you go to 25% efficiency in module level, consequently the cost becomes also very high in a single junction solar cell. So, the ultimate objective is that to still retain the efficiency high but even instead of a single junction if you have multi junction solar cell but if the cost becomes lower then that will be beneficial for us.

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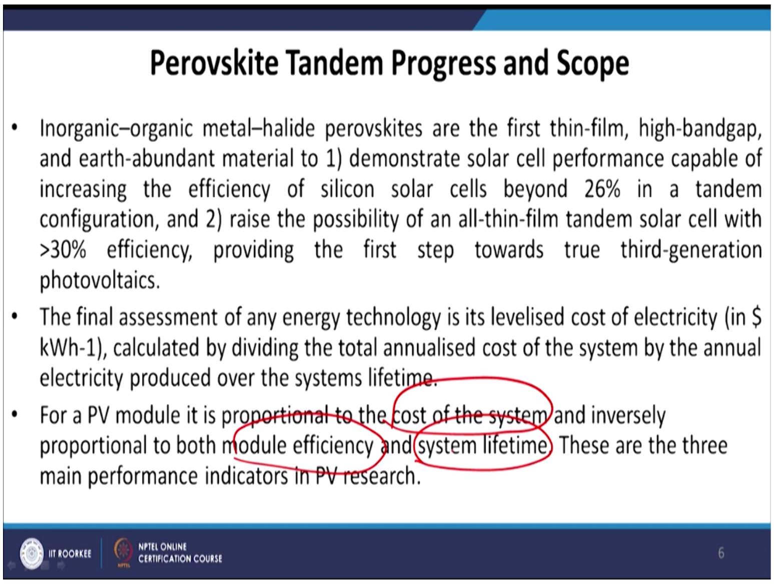

Now, inorganic-organic metal-halide perovskites are the first thin-film, high-bandgap and earth-abundant material to demonstration solar cell performance capable of increasing the efficiency of silicon solar cell beyond 26% in a tandem configuration and raise the possibility of an all-thin-film tandem solar cell with greater than 30% efficiency, providing the first step towards the true third-generation photovoltaics.

So, since in the silicon solar cell, we can get an efficiency greater than 25% in module but along with this if we use perovskite material and since we know that perovskite provides us some unique advantage like large bandgap or tunable bandgap and absorption coefficient is also very high, so if we combine these two different kind of solar cell then it is possible to reach an efficiency beyond 25% likely or 26% or 28% even greater than 30% efficiency.

The final assessment of any energy technology is its levelised cost of electricity. So, basically the efficiency and the cost relation is very important. So, we can increase the efficiency but for making a highly efficient solar cell if the cost of the production also increase very highly, then it is not a very feasible technology. So, wherever making the solar cell, we have to also keep in mind of the production process.

So, calculated by dividing the total annualized cost of the system by the annual electricity produced over the system lifetime. For a photovoltaic module, it is important or it is proportional to the cost of the system and inversely proportional to both module efficiency and system lifetime. These are the 3 main performances indicating in the PV research. So, first is the cost of the system when you make a PV module.

So, the PV module, the cost of the module is directly proportional and then it depends on the module efficiency and also the system lifetime like one instant how long it will last. So, these 3 factors like you know I said them like it forms a golden triangle. One is the efficiency, another is the lifetime and other is the cost. So, whenever any solar cell comes to a module part then for any kind of PV manufacturer they look for this triangle.

So, what is the cost of the solar cell, what is like you know lifetime or once installed in ambient condition how long it will last and also what will be the efficiency of the solar cell. So, these 3 parameters have to optimize simultaneously before bringing a technology into the market.

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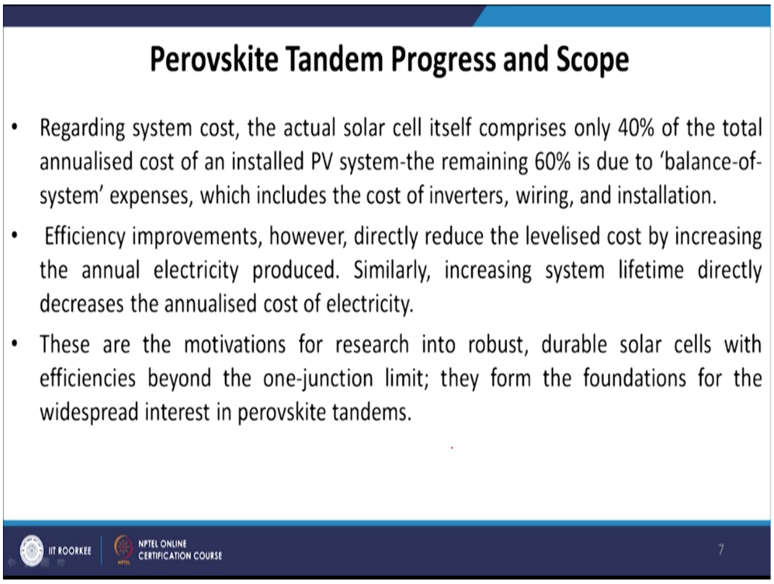

Regarding system cost, the actual solar cell itself compromised only 40% of the total annualized cost of an installed PV system, the remaining 60% is due to balance-of-system expenses, which includes the cost of inverters, wiring and installations. Efficiency improvements; however, directly reduce the levelised cost by increasing the annual electricity produced.

Similarly, increasing system lifetime directly decrease the annualized cost of electricity. These are the motivations for research into robust, durable solar cells with efficiencies beyond the one-junction limit; they form the foundations for the widespread interest in the perovskite tandems.

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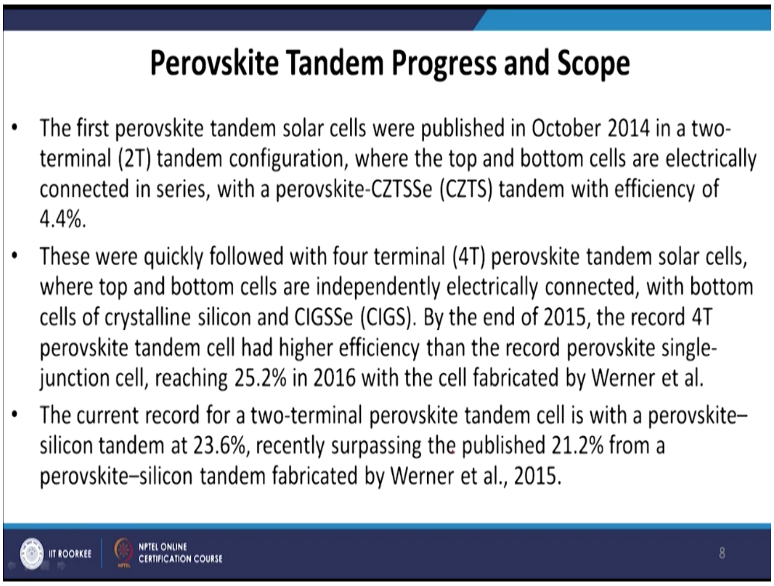

The first perovskite tandem solar cells were published in October 2014 in a two-terminal 2T tandem configuration, where the top and bottom cells are electrically connected in series, with a perovskite CZTSSe or CZTS tandem with efficiency of 4.4%. So, the first effort of making a tandem solar cell with perovskite was not in the silicon but with CZTS based solar cell.

So, we have taken a perovskite along with the CZTS and that solar cell gives us an efficiency of 4.4% not very high. These were quickly followed with four terminal perovskite tandem solar cells where top and bottom cells are independently electrically connected with bottom cells of crystalline silicon and CIGS solar cell. By the end of 2015, the record 4T perovskite tandem solar cell has a efficiency that is higher than the record perovskite single junction solar cell, reaching 25.2% in 2016 with the cell fabricated by Werner et al.

Now, when we make a two-terminal devices then the efficiency value was limited to that 4.4% but when he go for a four terminal devices where like you know the two devices were connected in the series and then by optimizing the device parameters this Werner’s group in 2015 they have reported an efficiency which crossed the single junction perovskite solar cell efficiency that is 25.2%.

The current record for a two-terminal perovskite tandem cell is with a perovskite silicon tandem that is at 23.6%. So, now instead of the CIGS solar cell if we use silicon as one of the component of the tandem, then the efficiency increases to 23%. Recently, surpassing the published 21.2% from a perovskite silicon tandem fabricated by Werner et al in 2015. So, even this silicon perovskite tandem solar cell has the potential of crossing the efficiency of almost any single junction solar cell.

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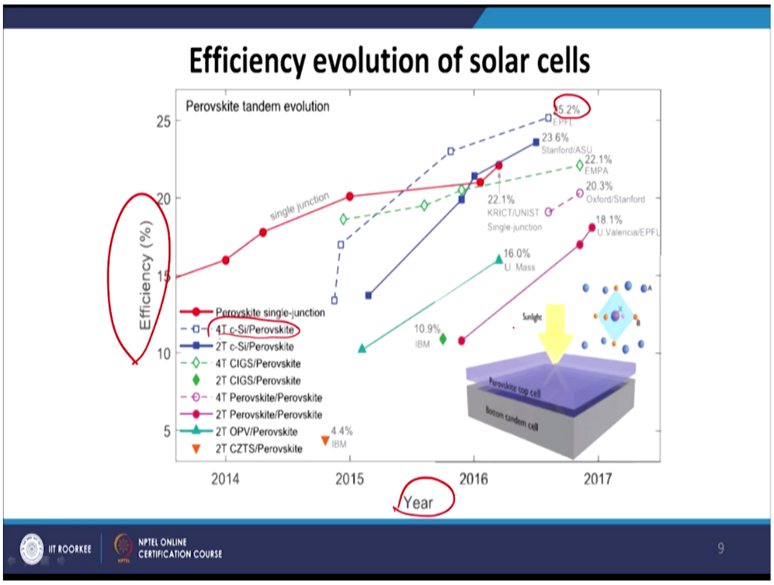

Now, this chart we have also discussed earlier in the beginning of the lecture when we talked about the different generations of the solar cell and here we are showing the efficiency revolutions of the solar cell and as you can see in the y-axis we have the efficiency in percentage and the x-axis is the year.

So, although it has been shown until 2017 so you can see that the perovskite single junction solar cell the efficiency is increasing but what about like you know the four terminal silicon perovskite solar cell, let us look at this graph. So, you see that the steep of the curve is very high, so the efficiency has been reported by an EPFL group at 25.2% okay. So, similarly like you know I mean this graph is showing a two-terminal single silicon perovskite tandem.

Then, there are four terminal CIGS perovskite tandem and then there are two-terminal silicon perovskite tandem.

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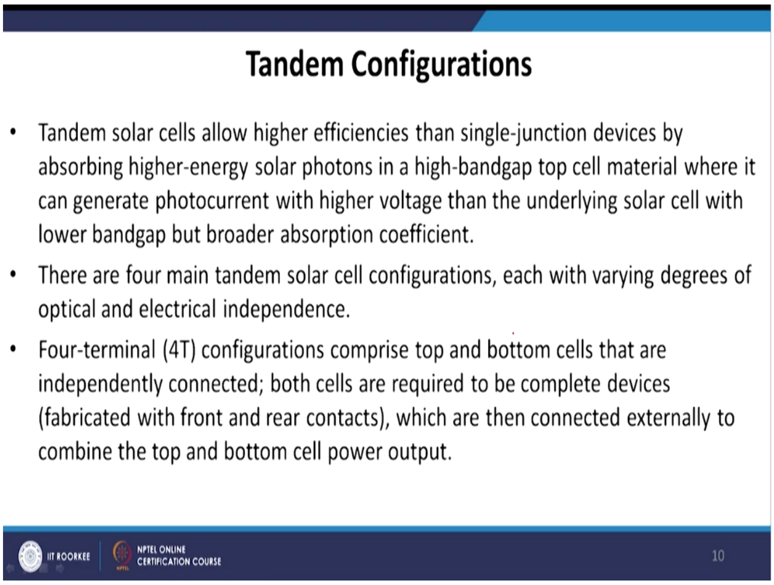

Tandem configurations; tandem solar cells allow higher efficiency than the single junction devices by absorbing high energy solar photons in a higher bandgap top cell material where it can generate photocurrent with higher voltage than the underlying solar cell with lower bandgap but broader absorption coefficient. So, usually that top solar cell is a high bandgap material. So, what is the advantage of using a high bandgap material?

Like if I have a perovskite silicon tandem, then we know that perovskite has a higher bandgap than the silicon. So, we will put the perovskite as a top layer. So, the advantage is that they can absorb the high energy solar photons and in the bottom layer like you know we put a, if the high energy solar photons is absorbed then high photo voltage is also or high photo current is also generated right.

And then the lower material in this case of silicon perovskite, silicon has a lower bandgap 1.1 electron volt like in comparison to the perovskite, so we put the silicon as a bottom layer which can absorbs the material with higher absorption coefficient. So, basically the idea is that we can cover all the electromagnetic spectrum both the visible range as well as the near IR range okay.

So, there are 4 main tandem solar cell configurations, we have already shown you the figures of all these 4 with varying degrees of optical and electrical independence. So, the parameters here is the optical and electrical independence. Now, you remember like you know when we discuss about the 4 different configuration, so sometimes we put a tunnel junction, sometimes we put a spacer layer.

So, what is the difference here between a tandem between a tunnel junction and a tandem spacer layer? So, the difference is their optical and electronic coupling. So, based on this optical and electronic coupling, since we have two different kind of materials so that means two different dielectric constant, so it is very important to couple the light from one of the solar cell to the another solar cell.

Four-terminal configuration compromise top and bottom cells that are independently connected; both cells are required to be complete device fabricated with front and rear electrode, which are then connected externally to combine the top and bottom cell power output. So, in four-terminal devices, the top terminal and the bottom terminal is to complete devices and then which is finally connected to two different bottom and top connected solar cell.

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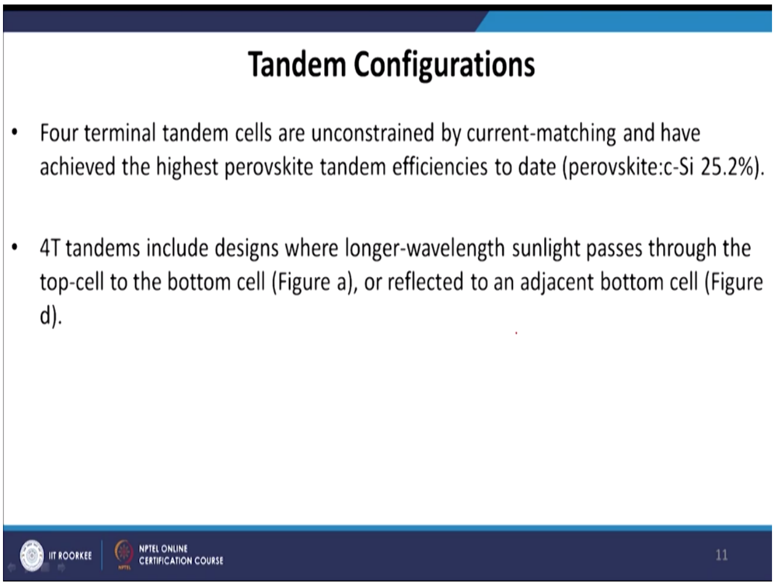

Four-terminal tandem solar cells are unconstrained by current-matching and having achieved the highest perovskite tandem efficiency to the date. For a perovskite single crystal silicon, it is almost 25.2% and four terminals tandem include designs where longer-wavelength sunlight passes through the top-cell to the bottom cell or reflected to an adjacent bottom cell.

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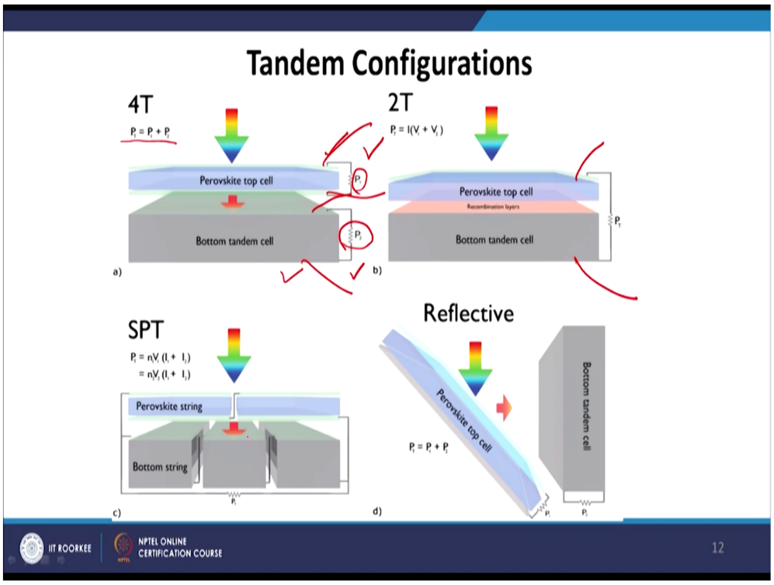

Look at this the device diagram of a four terminal tandem solar cell, you see here there is a perovskite tandem, here the light is falling from the top and then the bottom there is an another solar cell is there. So, this is a complete device, the top one is a complete devices right and so the load it is running or the efficiency it is giving let us say it is P1 and the bottom solar cell that is an another independent solar cell and that is also connected with an external load and the efficiency it is giving is P2.

So, P1 and P2 and we can think about there are two equivalent circuit which is connected by a series resistance, so the total efficiency will be PT= P1+P2 whereas in a two-terminal devices you see that there is a perovskite top cells is there and perovskite like you know bottom is a tandem cell but both of them has been sandwiched by a recombination layer. So, there is a difference between these two figures.

In one case, this is an individual solar cell, this is another individual solar cell and we connect them externally. Here, this the perovskite top layer and the bottom tandem solar cell, they are sandwiched with the recombination layer and one contact we take from here and another contact we take from here okay but here we are taking one contact from here, one contact from here, one contact from here, one contact from here.

So, this is actually an individual solar cell, this is an individual solar cell and finally we are combining the efficiency of the two solar cell but here this two solar cell one of them we are using as a top electrode and another one we are using as a bottom electrode. So, there is a significant difference between the configurations of this four terminal and two terminal devices.

So, we are also showing the reflective mode like if the peroxide is used as a top cell, the light falls on here then it is also possible the light the reflect and then coupled to the bottom tandem solar cells. Also, there is a possibility of the light to transmit through here. So, the light can be coupled either through the transmission or through the reflections.

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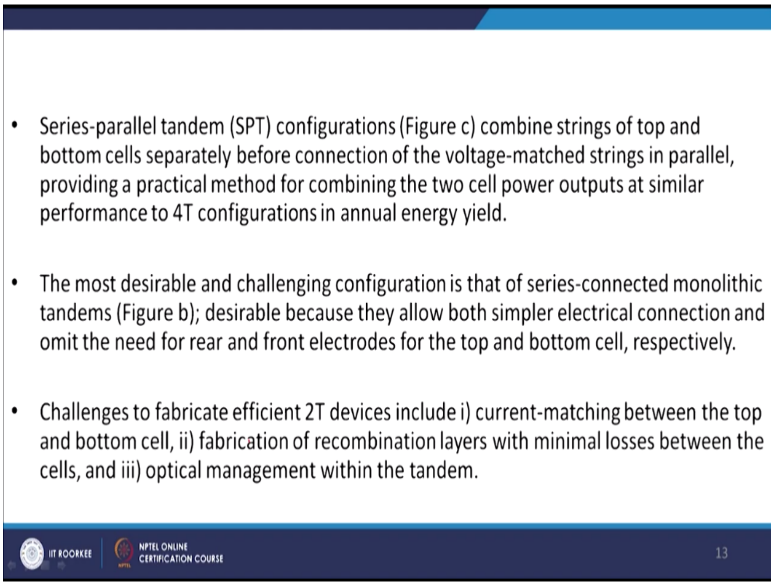

Now, series-parallel tandem or SPT configurations which is shown in the third figure, combine strings of top and bottom cells separately before connection of the voltage-matched strings in parallel, providing a practical method for combining the two cell power outputs at similar performance to four terminal configurations in annual energy yield.

The most desirable and challenging configuration is that of series-connected monolithic tandems figure b; desirable because they allow both simpler electrical connections and omit the need for rear and front electrodes for the top and bottom cell respectively. Challenges to fabricate efficient 2T devices include current matching between the top and bottom cells is very important.

If I have a 2T device or two-terminal devices, so it is very important to have a current matching between the top and bottom cells. Fabrication of the recombination layers with minimum loss between the cells and optical management within the tandem. So, if I use two-terminal devices, basically we have to use a recombination layer between the top and the bottom solar cell.

Now, the recombination layer as the name suggests it is supposed to do the recombination, so we have to use the recombination layer but also we have to make sure the recombination loss is less as possible and at the same time the optical coupling should be very higher.

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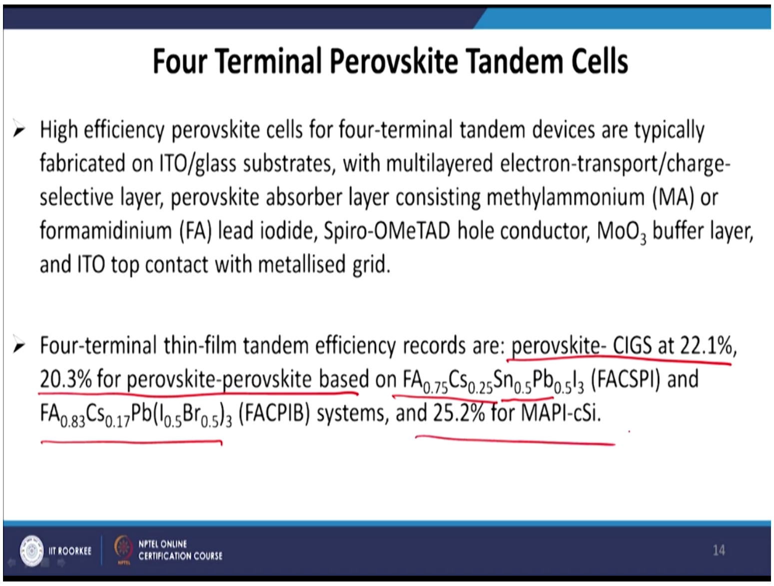

Now, high efficiency perovskite cells for four-terminal tandem devices are typically fabricated on ITO glass substrate with multi-layered electron-transport charge-selective layer, perovskite absorber layer consisting methylammonium or formamidinium lead iodide, Spiro-OMeTAD as a hole conducting material, moly trioxide, buffer layer and ITO top contact with metallised grid.

So, we are using ITO as a bottom contact and also a metallised ITO grid as a top contact. Four-terminal thin-film tandem efficiency records are for a perovskite CIGS solar cell, it is 22.1%, 20.3% for perovskite-perovskite based on the formamidinium and cesium, there are two double cation we are using here and then we are using two different metal Sn and lead and it was an iodine based devices and FA cesium lead iodine bromine systems and which has an efficiency of 25.2% for a MAPI crystalline silicon solar cell.

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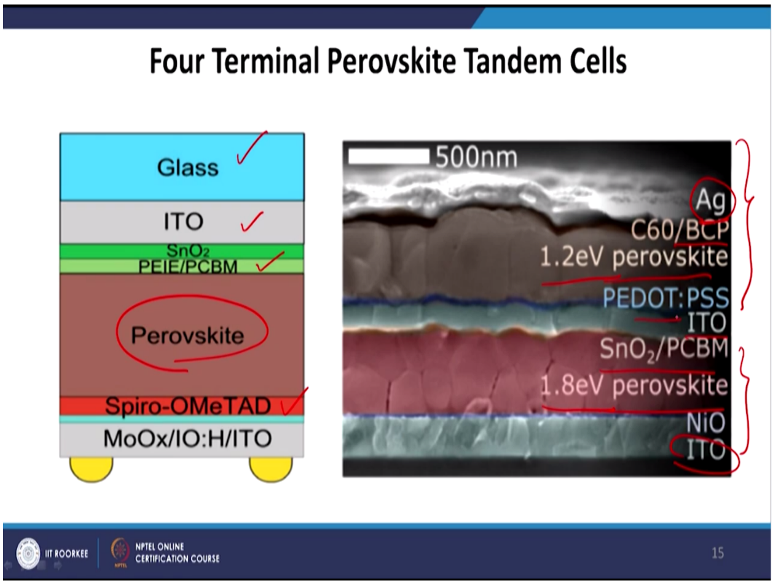

Now, you look at a four-terminal perovskite tandem cells, so here like you know as I said that there is a glass layer and then this is ITO layer okay and then we put the perovskite the active layer between a PCBM layer which acts like an electron acceptor and also a Spiro-OMeTAD layer and finally there is a MoOx coated ITO layer. So, if I take a cross-sectional SEM image, the different layers is showing here.

This is the perovskite and this is the SnO2 or PCBM layer, ITP, PEDOT PSS and then again we are using another perovskite with 1.2 electron volt and C60 BCP with here we are using gold sorry here we are using the silver and here we are using the ITO. So, basically this is that two different perovskite we are using; one is 1.8 electron volt perovskite, one is 1.2 electron volt perovskite.

Now, we know to make a perovskite solar cell let us say for the top solar cell, this is the first solar cell. So, we have an ITO layer and then PEDOT PSS right, then the perovskite which is a bandgap of 1.2 electron volt then C60 and the BCP and then the Ag layer. So, that is a PIN geometry of a perovskite solar cell. Now, you look at the bottom layer here, ITO and then nickel oxide, then 1.8 electron volt perovskite, then SnO2 or PCBM we use.

And finally, we are using this ITO level, the second ITO level which is acting like a connecting level and also as a top electrode of the bottom solar cells okay. So, now these two solar cells have been now connected with each other.

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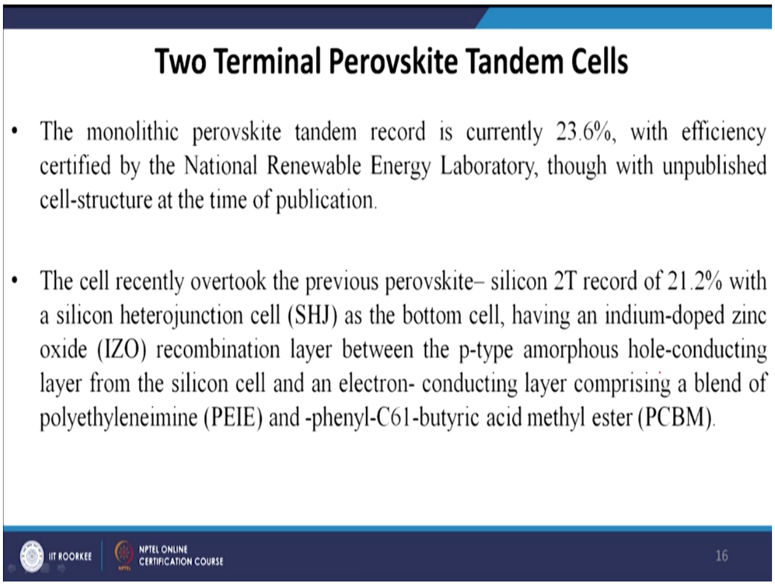

What about two-terminal perovskite tandem solar cell? The monolithic perovskite tandem record is currently 23.6%, with efficiency certified by National Renewable Energy Laboratory NREL, though with unpublished cell-structure at the time of the publication. The cell recently overtook the previous perovskite silicon 2T record of 21.2% with the silicon heterojunction cell as the bottom cell, having an indium-doped zinc oxide recombination layer between the p-type amorphous hole-conducting layers from the silicon cell.

And an electron conducting layer compromising a blend of polyethyleneimine and polyethylene C60 butyric acid methyl ester PCBM.

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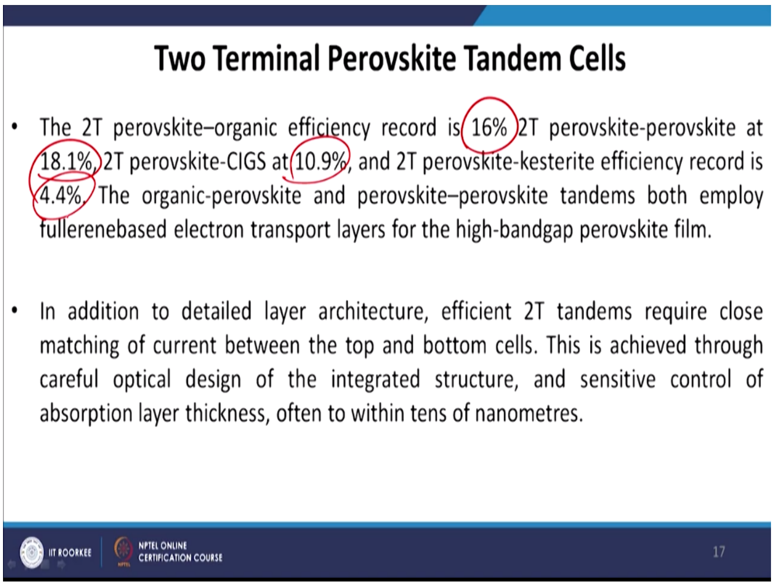

The two-terminal perovskite-organic efficiency record is 16%, instead of perovskite, instead of silicon, if I use perovskite organic solar cell like perovskite BHJ tandem, then the efficiency is 16%. So, that is for the two-terminal perovskite- perovskite is 18.1% and two-terminal perovskite-CIGS is 10.9% and two-terminal perovskite-kesterite efficiency record is 4.4%. The organic perovskite and perovskite tandems both employ fullerene based electron transport layers for the high bandgap perovskite material.

Now, if the bandgap increase then we use fullerene based acceptor as one of the charge transport layer. In addition to the detailed layer architecture, efficient two-terminal tandem requires close matching of current between the top and bottom cells. This is achieved through careful optical design of the integrated structure and sensitive control of the absorption layer thickness, often to within tens of nanometers.

So, not only the bandgap matching but optical coupling is also very important because we have to make sure that there is no recombination loss or also we have to make sure whatever the light or photo current which have been generated from the first layer that efficiently coupled with the second layer.

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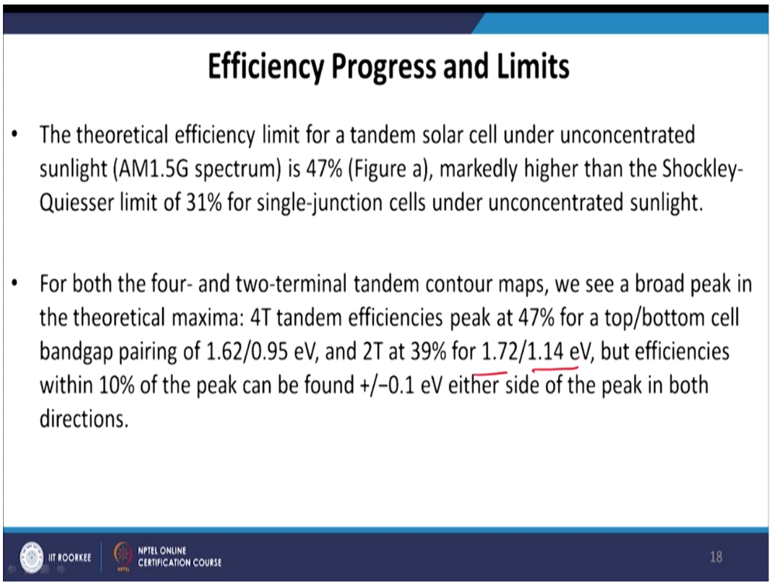

Now, if we look at the efficiency progress and some of the limits of that, the theoretical efficiency limit for a tandem solar cell under unconcentrated sunlight that is AM1.5G spectrum is 47% that is markedly high than the Shockley-Quiesser limit of 31% for a single junction solar cell under unconcentrated sunlight.

So, you see that the theoretical limit for a tandem solar cell is 47% but the Shockley-Queisser limit for a single junction solar cell is 31%, so it is possible to reach an efficiency of much higher than the single junction solar cell in a tandem solar cell. For both the four and two terminal tandem contour maps, we see a broad peak in the theoretical maxima; four-terminal tandem efficiency peak is at 47% for a top bottom cell bandgap pairing 1.62 electron volt and 0.95 electron volt.

And for two-terminal devices, the maximum theoretical efficiency possible is 39%. If we use two different materials, one having a bandgap of 1.72 electron volt, another having a bandgap of 1.14 electron volt but efficiencies within 10% of the peak can be found with +-0.1 electron volt either side of the peak in both directions.

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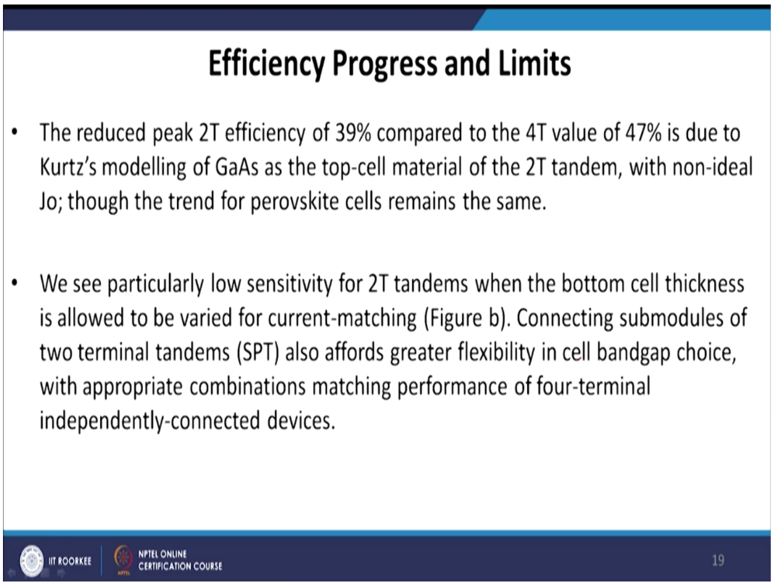

So, the reduced peak 2T efficiency of 39% compared to the four-terminal value of 47% is due to the Kurtz's modeling of the gallium arsenide as the top cell material of the 2T tandem with non-ideal short-circuit or the intrinsic current Jo through the trend for perovskite cells remains the same. So, if I use two-terminal devices, the theoretical maximum efficiency is less than four-terminal devices.

And the reason behind that, we use the gallium arsenide layer on the top where there is a loss of the light in two-terminal devices but still whether it is a two-terminal or a four-terminal, the efficiency is still higher than a maximum theoretical limit of a single junction solar cell. We see particularly low sensitivity for two-terminal tandems when the bottom cell thickness is allowed to be varied for current matching.

Connecting some modules of two-terminal tandems also afford greater flexibility in cell bandgap choice with appropriate combinations matching performance of four-terminal independently-connected devices.

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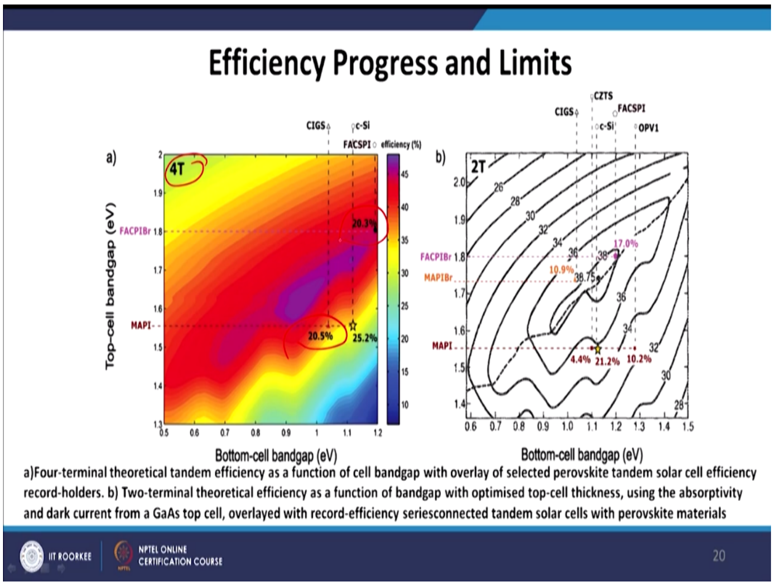

Now, here we are looking a contour map of a four-terminal and the two-terminal devices, you see that the four-terminal theoretical tandem efficiency as a function of the cell design with overlay of the selected perovskite tandem solar cell efficiency record-holders. So, if I put a bottom cell bandgap here and the y-axis is the top cell bandgap, so in a 4T cell often it is very high, the contour map is showing that this efficiency contour is in a higher region than comparison to the other case.

Now, there is possible that you know I mean if you use moly like in MAPbI3 like CH3NH3 lead iodide solar cell and if you use like you know FACPIBr solar cell. So, as we go from one to the another band, if we change the, tune the bandgap, so this contour map is showing that the efficiency can be tuned over a very broad range.

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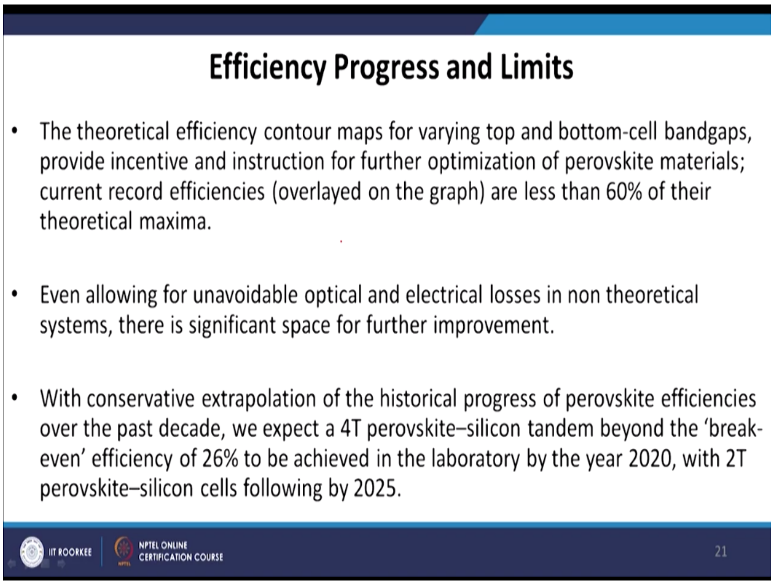

Now, the theoretical efficiency contour maps for varying top and bottom-cell bandgaps provide incentive and instruction for further optimizations of the perovskite materials; current record efficiency overlay on the graph are less than 60% of their theoretical maxima. Even allowing for unavoidable optical and electrical loss in non-theoretical system, there is a significant space for further improvement.

Well, I mean I know that or each of us know that I mean so in a tandem solar cell apart from the material design or material architecture, the optical spacing that plays a very important role, so that is why it is not always possible to reach the theoretical maximum efficiency limit.

So, there is a limit we can go because of that but still like you know by changing the bandgap, by doing a morphology (()) (29:40), by doing a combination approach of different cationic site and anionic site in the perovskite, along with a multi-junction silicon solar cell, it is always possible to improve the efficiency further and further, so there is a scope of improvement.

With conservative extrapolation of the historical progress of the perovskite efficiencies over the past decade, we expect a four-terminal perovskite single tandem solar cell beyond the break-even efficiency of 26% to be achieved in the laboratory by the year of 2020, within two-terminal perovskite solar cell following by 2025. So, if we look at the trend, the way the perovskite solar cell has been revolutionized within the last 5, 6 years.

So, if we follow the same trend, it is very much possible that the efficiency of a perovskite silicon tandem can reach a much higher number very soon.

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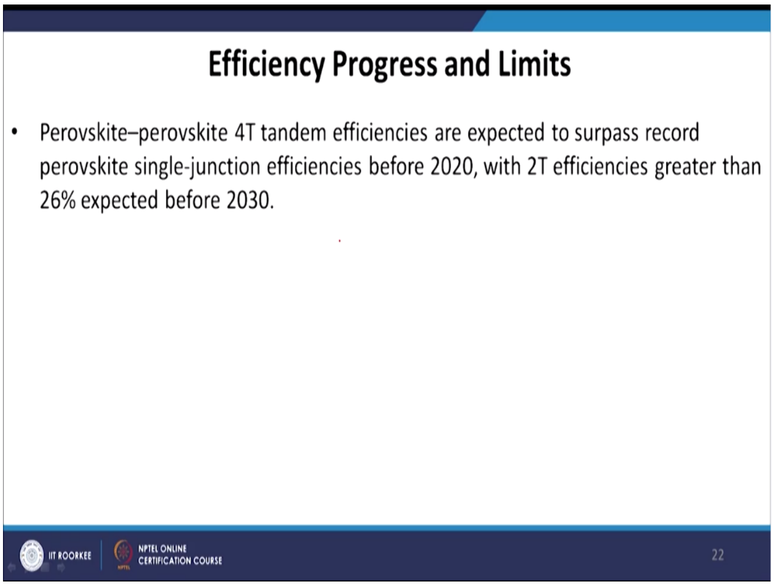

But there are also some limits of course, perovskite-perovskite four-terminal tandem efficiency are expected to surpass record perovskite single-junction efficiency before 2020 and with 2T efficiency greater than 26% expected before 2030.

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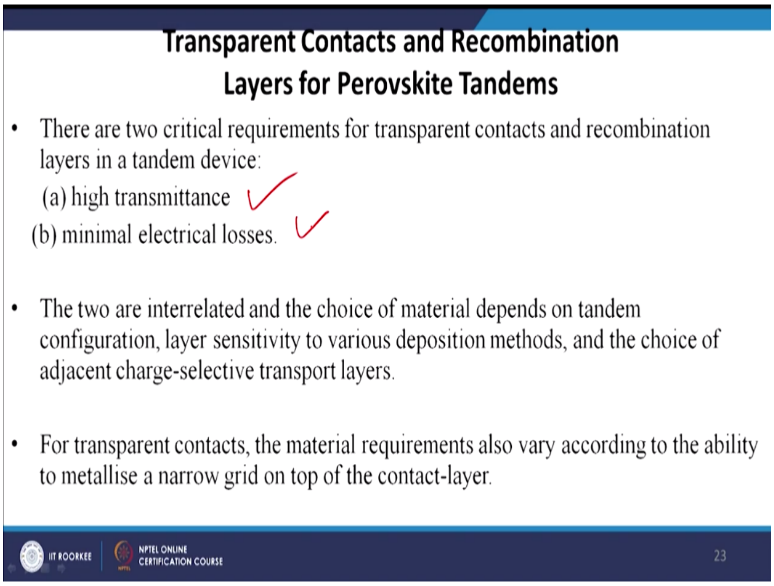

There are lots of research groups which are now working on this area. Now, what about the transparent contacts and the recombination layer for the perovskite tandems because we are talking again and again about this recombination layers and we say that optical and electrical coupling plays a very important role in perovskite devices. Now, there are two critical requirements for transparent contacts and recombination layers in tandem devices.

One is the high transmittance, so the light should be able to pass without any obstacle and second is that minimal electrical losses so the electrical loss should be also minimum. So, first is an optical properties, second is an electrical properties. Now, the two are interrelated and the choice of material depends on tandem configuration, layer sensitivity to various depositions methods and the choice of adjacent charge-selective transparent layer or transport layer.

For transparent contacts, the material requirements also vary according to the ability to metallise a narrow grid on top of the contact-layer. Now, since we are using in both case the ITO as a top and bottom contact, only we are putting a metallised grid on the top, so basically we have to choose a contact, transparent contact in such a way that we will be able to evaporate or we will be able to deposit a very narrow grid on that top contact.

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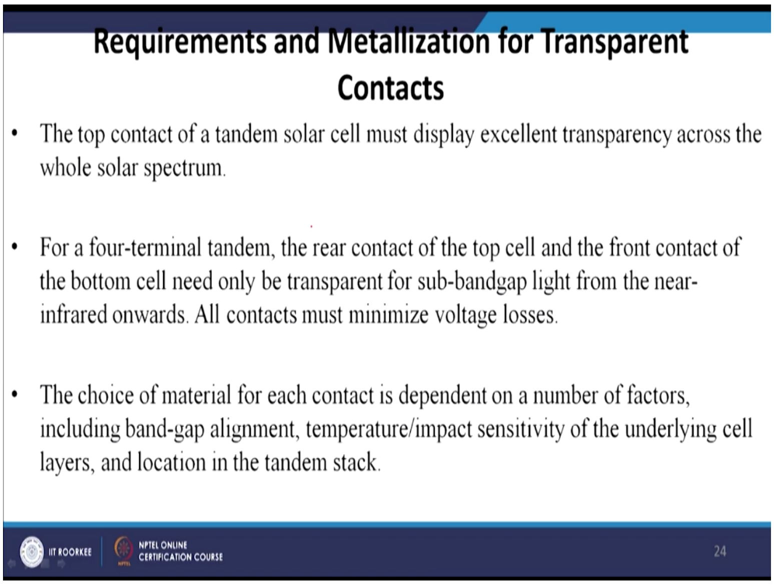

Now, the top contact of a tandem solar cell must display excellent transparency across the whole solar spectrum. For a four-terminal tandem, the rear contact of the top cell and the front contact of the bottom cell need only be transparent for sub-bandgap light from the near-infrared onwards. The choice of material for each contact is dependent on a number of factors including bandgap alignment, temperature impact sensitivity of the underlying cell layers and location in the tandem stack.

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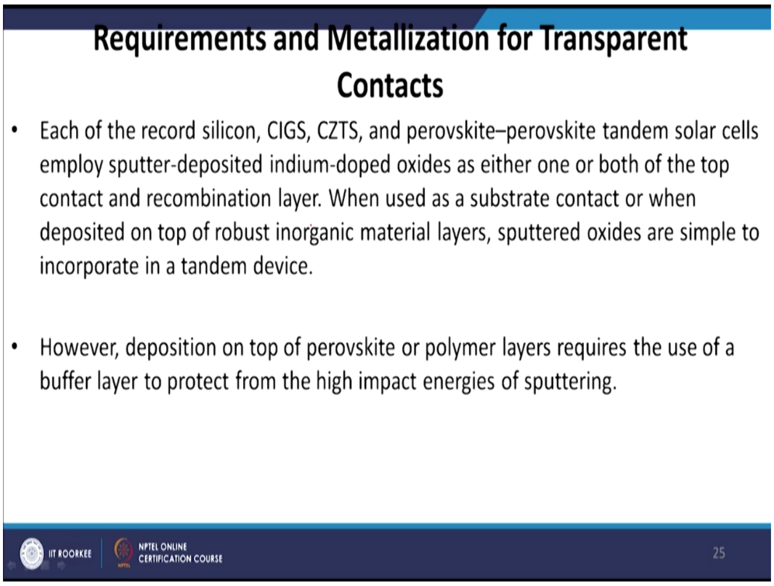

Each of the record silicon, CIGS, CZTS and perovskite- perovskite tandem solar cells employ sputter-deposited indium-doped oxide as either one or both of the top contact and recombination layer. So, in both of these cases, we use ITO as well as a top contact and bottom contact also as a spacer layer or as a recombination layer.

When used as a substrate contact or when deposited on top of robust inorganic material layers, sputtered oxide are simple to incorporate in a tandem devices. However, deposition on top of perovskite or polymer layers requires the use of a buffer layer to protect from the high impact energies of the sputtering. So, in the top contact perovskite layer, if we put an ITO and then if we sputter actually the ITO on an inorganic material, so there is a possibility of the penetration.

So, the device can be damaged. So, we have to be very careful while sputtering the ITO on top of the inorganic electrode or inorganic material for the second component of the tandem solar cell.

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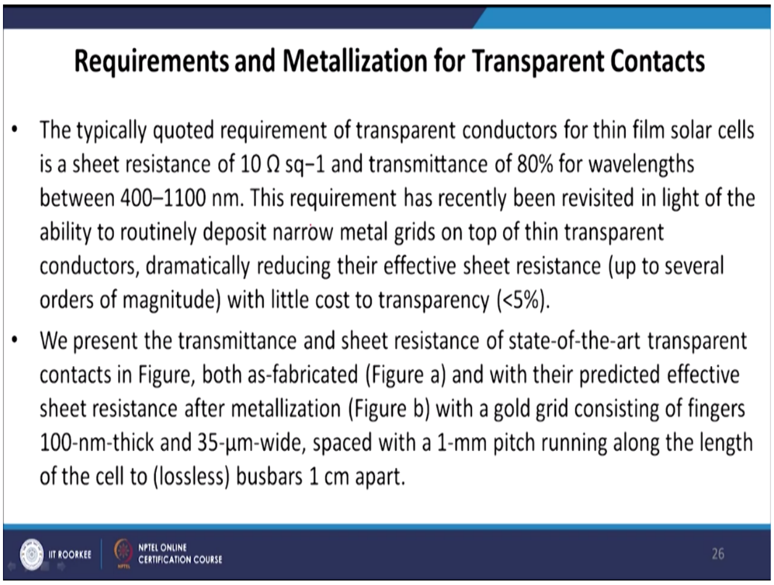

Now, typically the coated requirement of transparent conductors for thin film solar cells is a sheet resistance of 10 ohm per square centimeter and transmittance of 80% for wavelengths between 400 to 1100 nanometer. This requirement has recently been revisited in light of the ability to routinely deposit narrow metal grids on top of the thin transparent conductors dramatically reducing their effective sheet resistance after several orders of magnitude with little cost to transparency less than 5%.

We present the transmittance and sheet resistance of state-of-the-art transparent contacts in the next figure both as fabricated and with their predicted efficient sheet resistance and metallizations with a gold grid consisting of fingers 100 nanometer thickness and 35 micron wide, spaced with the 1 millimeter pitch running along the length of the cell to lossless busbars 1 centimeter apart.

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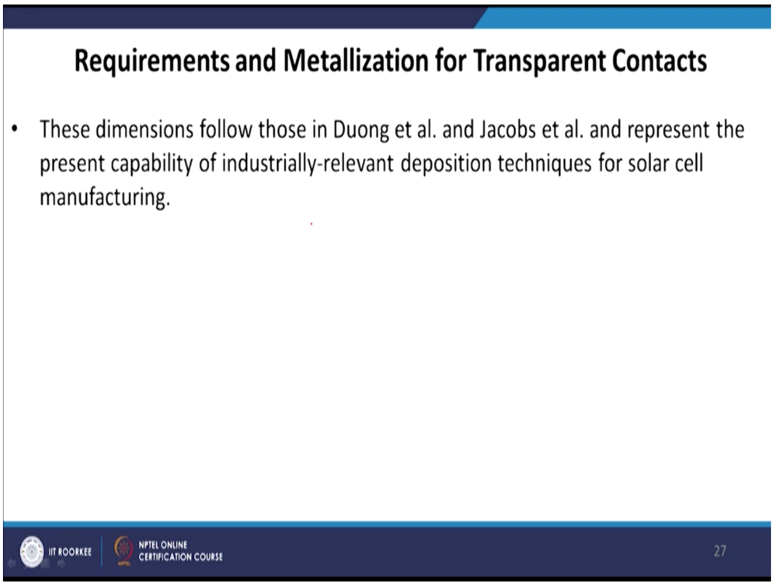

So, let us look at the figure in the next diagram. These dimensions follow those in Duong et al's and Jacobs et al's paper and represent the present capability of industrially-relevant deposition techniques for solar cell manufacturing.

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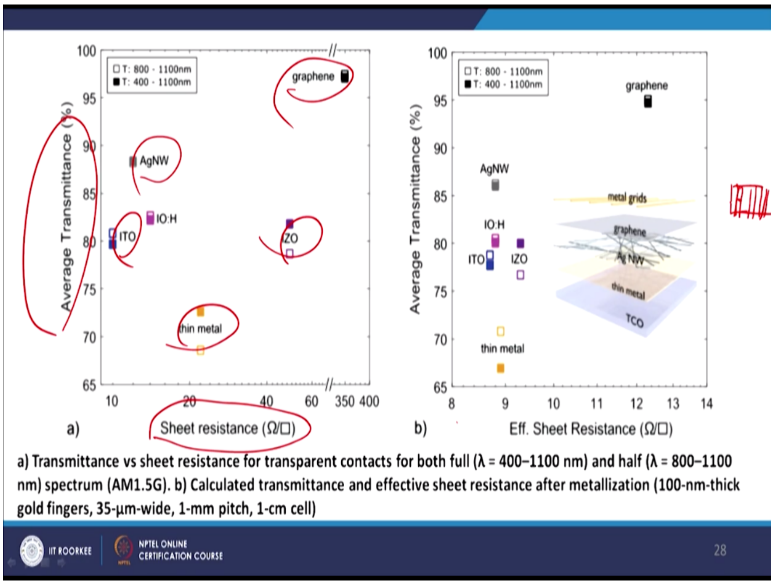

Now, you see that if we look at this graph, so there are so many parameters to optimize. Now, we can use the ITO, we can use graphene layer, we can use thin metal, we can use IZO or we can use the silver nanowires. Now, if we use the different layers, so what the properties is going to change, the transmittance and also the sheet resistance. So, we have to make sure the contact has a very high transmittance over the whole solar spectrum.

And at the same time, the sheet resistance should be very low so that the sheet resistance or the series recombination would be very low and on the right hand side again like you know we are showing that as a function of the effective sheet resistance. If you change it from 8 to 10 to 12 to 14, you see that how does the transmission is also changing for the same kind of material.

So, while designing the material, so it depends upon for example if I have a metal, if I have like in a top contact of ITO and if I have to put a interdigitated like this kind of narrow finger electrode on the top, so it depends upon what is the width of this finger electrode, what is the spacing between the successive electrode, what is the length between electrode, so all of these things has to be optimized before getting a high efficiency solar cell.

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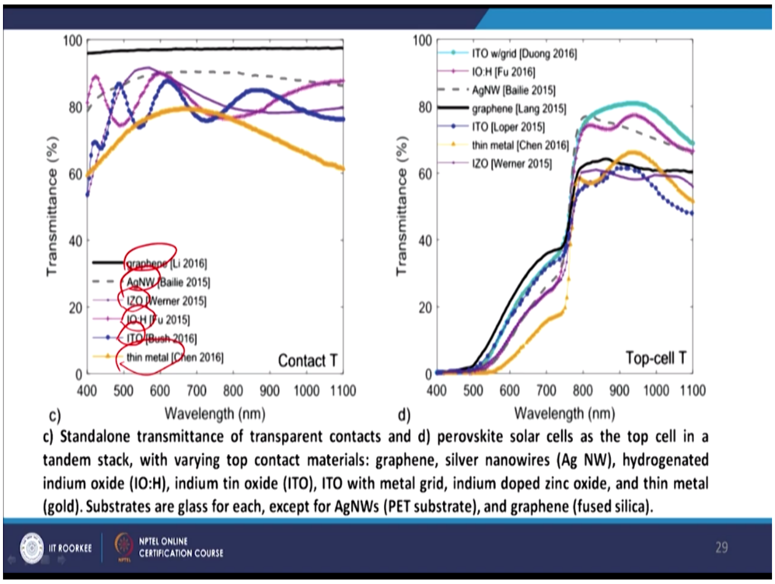

Again, the standalone transmittance of the transparent contacts is shown in the following figure like here the transmittance versus wavelength is showing for a graphene layer, for a silver nanowire, IZO, ITO and thin metal layer. Similarly, the transmittance versus wavelength layer is showing for different types of ITO, AgNW, graphene, ITO and IZO layer.

So, you can use graphene also as a conducting electrode or as a transparent electrode, you can use silver nanowire, you can use IZO layer, you can use IOH layer, you can use ITO layer or even you can use a very semi-transparent thin metallic layer also and if we use different layers, so how the transmittance will be going to vary with the sheet resistance that we have to record by doing an absorption spectroscopy and corresponding the resistivity measurement.

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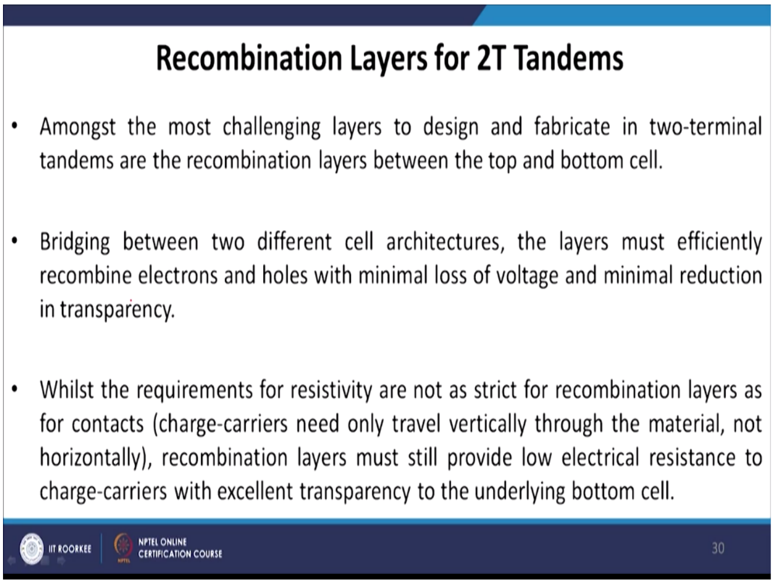

Now, the recombination layers for two-terminal tandems amongst the most challenging layers to design and fabricate two-terminal tandems and the recombination layers between the top and bottom cell. Bridging between the two different cell architectures, the layers must efficiently recombine electrons and holes with minimum loss of voltage and minimum reduction in transparency.

Obviously, when we put a transparent layer between the top contact and the bottom solar cell or top solar cell and bottom solar cell, we have to make sure that the transparency loss is as minimum as possible and the current or voltage loss at the interface is as minimum as possible. While the requirements for resistivity is not as strict for recombination layer as per contacts.

Recombination layer must still provide low electrical resistance to charge carriers with excellent transparency to the underlying bottom cells, a factor which we have already discussed.

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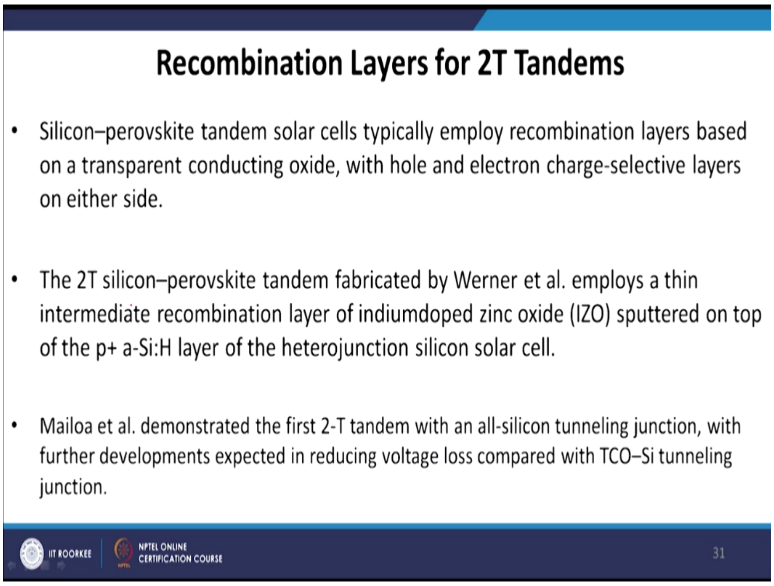

Now, silicon-perovskite tandem solar cells typically employ recombination layer based on a transparent conductive oxide with hole and electron charge-selective layers. The two-terminal silicon-perovskite tandem fabricated using an intermediate recombination layer of indium-doped zinc oxide also or sputtered on the top of a p-doped amorphous silicon layer of the heterojunction silicon solar cell or also this can be used by a TCO silicon tunneling configuration.

So, there are different configurations possible for making four-terminal or two-terminal devices that is what we are describing here.

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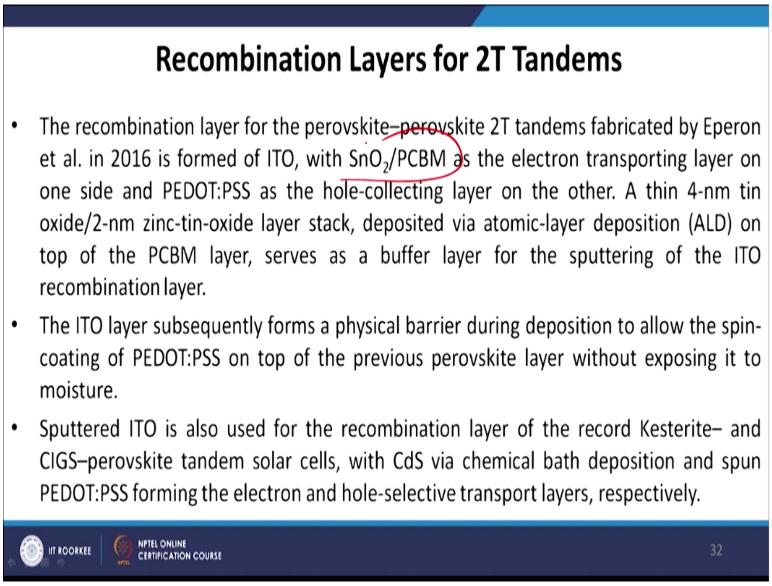

Similarly, the recombination layer for the perovskite-perovskite two-terminal tandems fabricated by another group which use the ITO with SnO2 PCBM as an electron transport layer. The ITO layer, they form a physical barrier between the deposition to allow the spin-coating of PEDOT PSS layer and sputtered ITO layer is also used for the recombination layer of the record kesterite and CIGS perovskite tandem solar cell with CdS via chemical bath depositions.

And then PEDOT PSS a hole transporting material was PIN coated forming an electron and hole selective layer. So, the bandgap matching is also very important.

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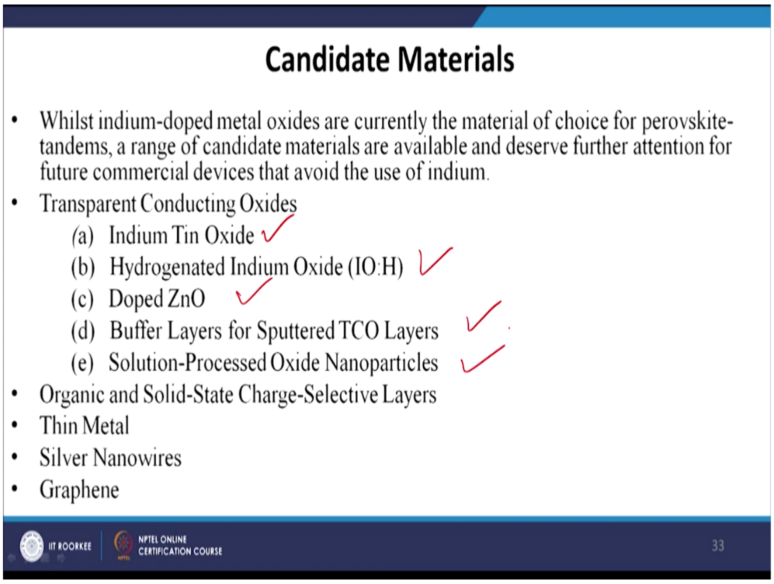

Now, what are the efficient or whatever the ideal candidate materials for making a tandem solar cell. While the indium-doped metal oxides are currently the material of choice for perovskite tandems, a range of candidate materials are available and deserve further attention for further commercial devices that avoid the use of indium. Now, there are several transparent conductive oxide can be used.

For example, ITO or indium-doped tin oxide glass substrate, hydrogenated indium oxide, doped zinc oxide, buffer layer for the sputtered transparent conductive oxide layer or solution-processed oxide nanoparticle. Organic and solid-state charge-selectively layers, thin metal, silver nanowires and graphene. Graphene is also nowadays used very efficiently to make a transparent conductive layer.

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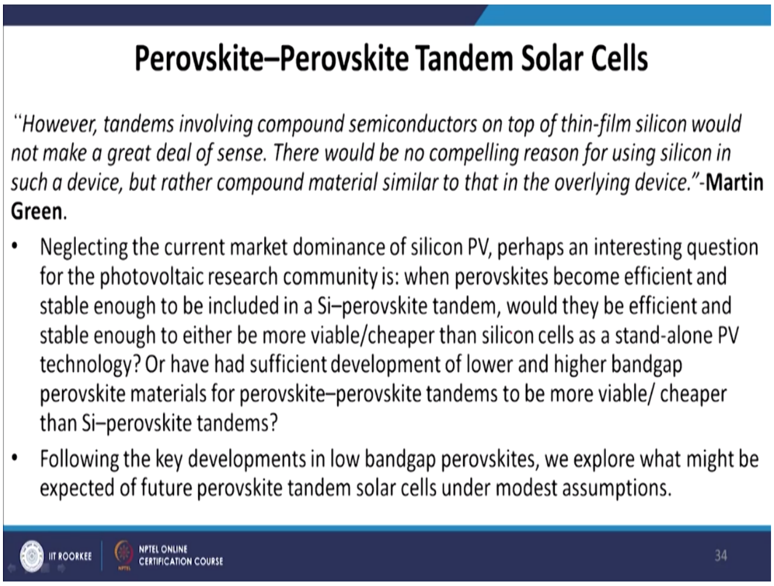

Now, however the tandem involving compound semiconductors on top of thin-film silicon would not make a great deal of sense. There would be no compelling reason for using silicon in such a device, but rather compound material similar to that in overlying device. That is a famous quote by Martin Green.

So, what he has mentioned here that neglecting the current market dominance of the silicon photovoltaics perhaps an interesting questions for the photovoltaic research communities when perovskite become efficient and stable enough to be included in a silicon perovskite tandem, would they be efficient and stable enough to either be more viable or cheaper than silicon solar cell as stand-alone PV technology?

Or have the sufficient development of lower and higher bandgap perovskite materials for perovskite- perovskite tandems to be more viable cheaper than silicon perovskite tandem. Now, this is still an open question whether perovskite- perovskite tandem is more viable option or perovskite silicon tandem will be a more viable option. Following the key developments in the low bandgap perovskite, we explore what might be expected of future perovskite tandem solar cell under the modest assumptions.

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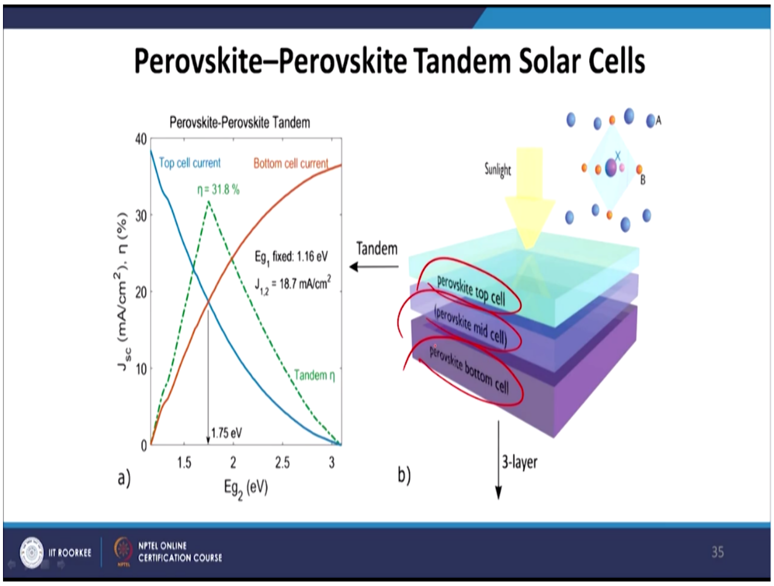

So, here if we take a perovskite- perovskite tandem, you see that the current is changing with the bandgap. So, if we go from 1.5 to a larger bandgap, so the efficiency with the top cell and bottom cell, it is decreasing right. So, it depends on a suitable combination like for example here the perovskite top cells and perovskite bottom cells, so far that was used as a tandem solar cell.

But in between if you also use a perovskite mid cell, perovskite mid cell with the variable bandgap then like there are 3 perovskite devices in my tandem solar cell, then it is possible to cover the whole electromagnetic spectrum provided like you know we have a suitable bandgap matching and the cells are very stable.

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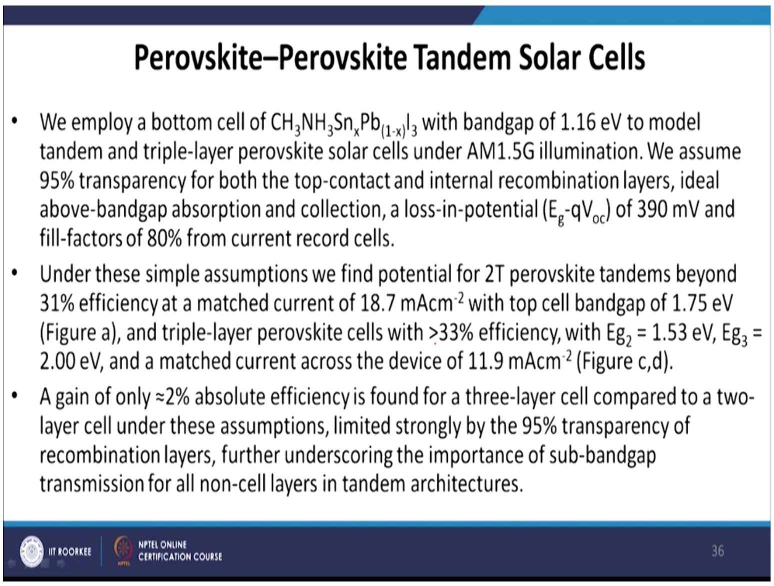

So, we employ a bottom of the CH3NH3 lead iodide with bandgap of 1.16 electron volt to model tandem and triple-layer perovskite solar cells, under this simple assumptions, we found that potential for a 2T perovskite tandem even can reach beyond 30%, 31% efficiency and a gain of only 2% absolute efficiency is found for a three-layer cell compared to a two-layer assumption limited strongly by the 95% transparency of the recombination layer.

Now, instead of 2% two-layer devices, if we go to the three-layer devices, there is an increase in efficiency but there is also still a problem is that once we increase the number of the solar cells, so basically we have an interface. So, at the interface, there is a recombination, so now this recombination or the transparency loss also has to be considered while increasing the different layers of the perovskite solar cell.

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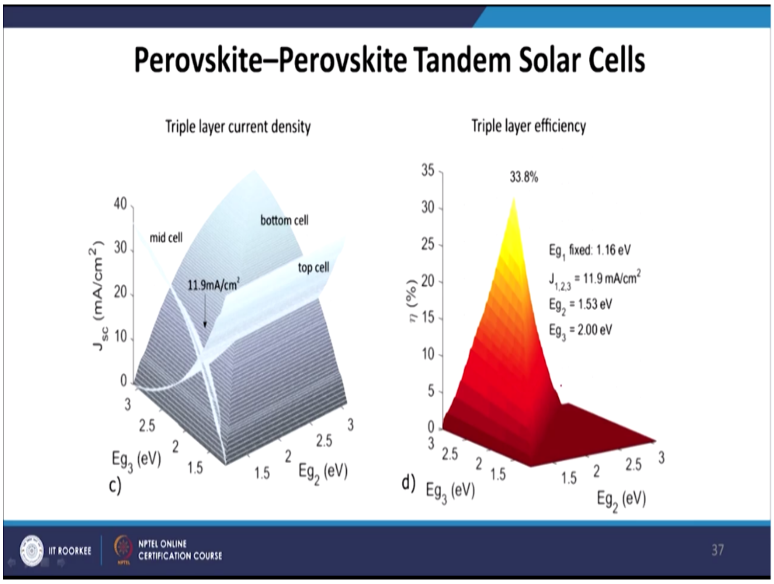

For example, this graph is showing a triple layer current density and here the corresponding triple layer current efficiency is shown here.

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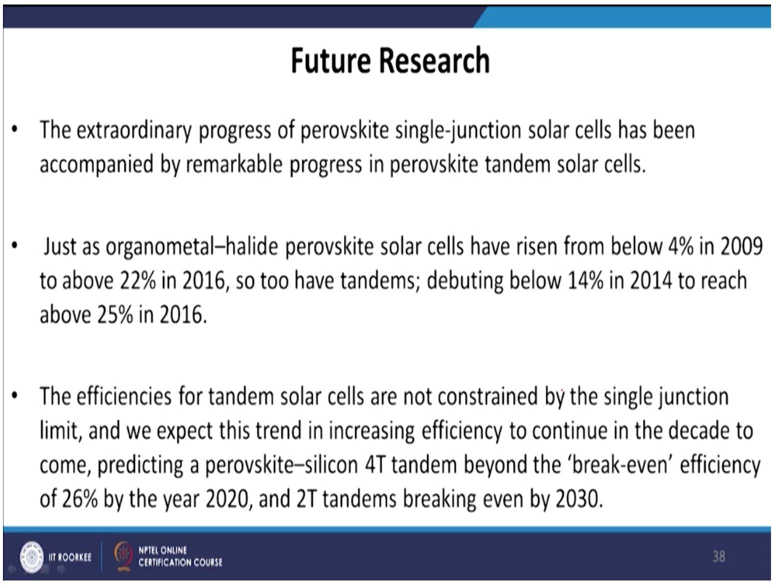

Now, what is the future of this field? Now, the extraordinary progress of the perovskite single junction solar cell has been accompanied by the remarkable progress in the perovskite tandem solar cell. After the discovery of the perovskite tandem solar cell, now people are thinking it is possible to bring in the market and perhaps it can compete with the silicon module.

Just as organometal-halide perovskite solar cell has risen from 4% to 22% or nowadays I mean today's number is 23% and this number is changing every other days. So, starting below from 14% to reach 25% in 2016 that we have observed in the case of tandem. So, probably we can be optimistic that very soon we will be able to reach 35% or even 40%.

The efficiency for tandem solar cells are not constrained by the single junction limit and we expect the trend to be increasing efficiency to continue in the decades to come, predicting a perovskite silicon four-terminal tandem devices to break the break-even efficiency of 26% and two-terminal devices by 2030.

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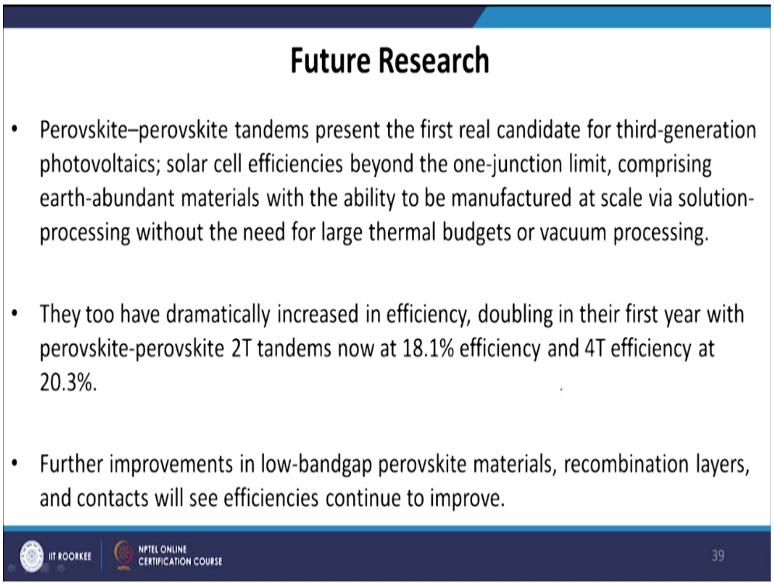

Now, it is possible to increase the efficiency even more than 30%, perovskite-perovskite tandem present the first real candidate for a third-generation photovoltaic solar cell beyond the one-junction limit compromising the earth abundant material with the ability to be manufactured at a large scale. They have dramatically increased the efficiency and also further improvements in the low bandgap materials along with the optimizations of the recombination layer can further improve the efficiency beyond 30%.

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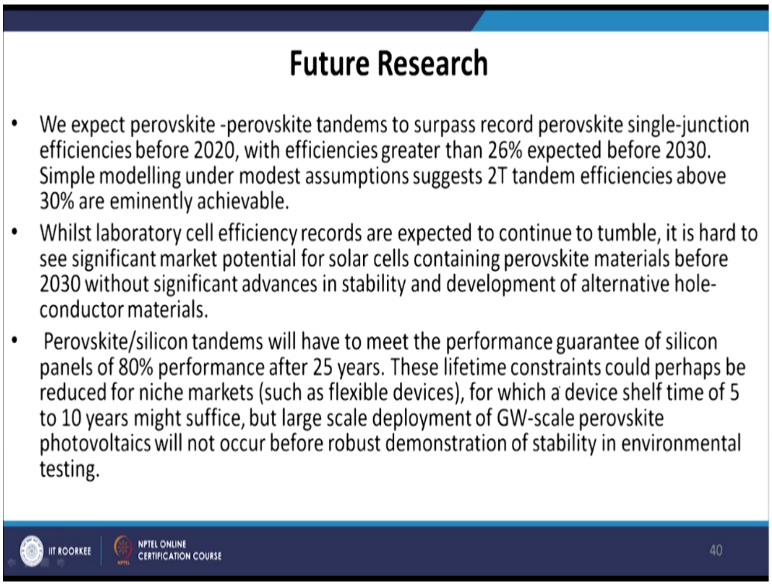

Similarly, we expect the perovskite-perovskite tandem to overcome the efficiency of 26% or to reach to 20 or 30% by 2030. Whilst laboratory cell efficiency are expected to be very high but when you make a module, the module efficiency is always less from the laboratory efficiency. So, while we make a module then we have to consider the various factors.

Perovskite silicon tandem will have to meet the performance guarantee of the silicon panels of 80% performance after 25 years.

Yes, so again remember the triangle, not only the efficiency or not only the cost but the lifetime also is very important. Now, silicon has passed the test like you know silicon keeps its efficiency or its performance more than 80% for a long period of time 25%. So, the silicon perovskite tandem also has to pass that test.

So, once installed it should be also able to keep its performance for a quite a long time without any loss of the efficiency, so without any loss of performance, that is also a significant factors need to be optimized before commercial license of this technology.

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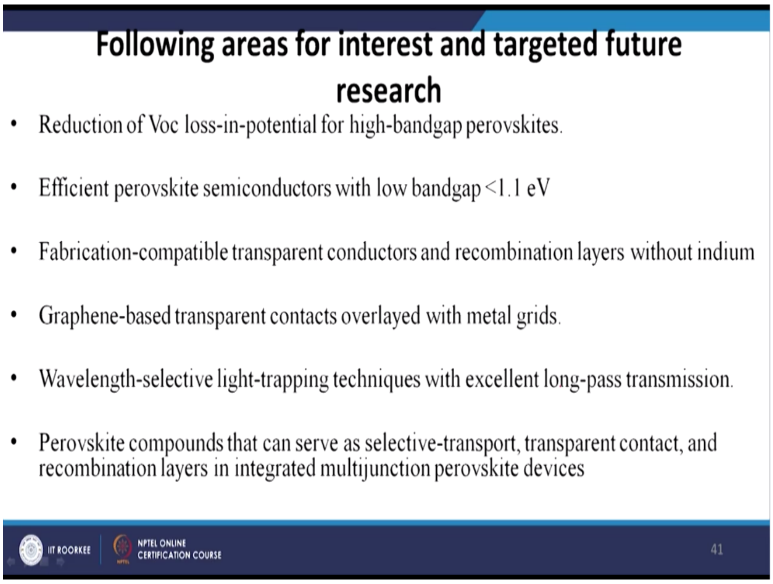

Now following areas are interest and the target for the future research, maybe some of you are might be interested. One is the reduction of the Voc value, loss in potential for high bandgap perovskite material, to develop efficient perovskite semiconductors with a bandgap less than the silicon that is 1.1 electron volt and then fabricates compatible transparent conductors and recombination layer to develop graphene based transparent layer.

And then wavelength-selective light-trapping layer and perovskite compounds that can serve as a selective transport and as well as a recombination layer in a multi-junction perovskite solar cell.

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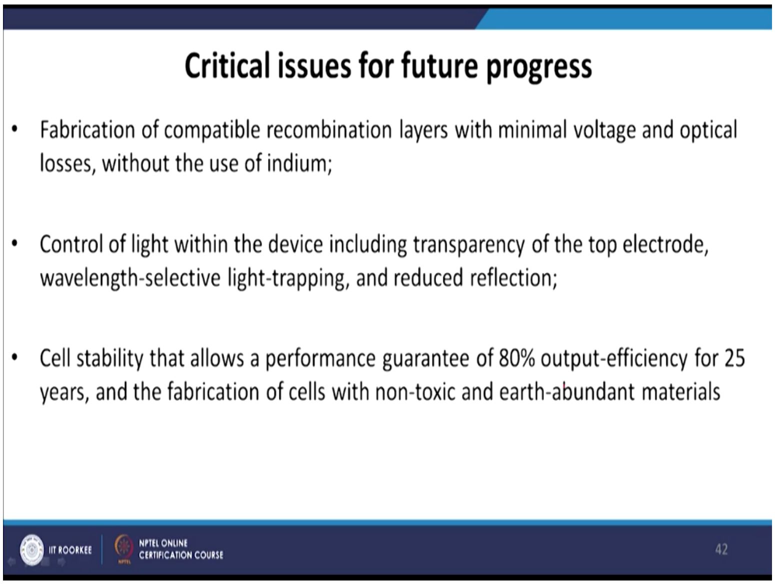

So, there are some critical issues also there, first this fabrication of the compatible recombination layer with minimum voltage loss is one of the problem and we do not need to use the indium in the future. Control of light with the device including the transparency of the top electrode and finally the cell stability that allows a performance guarantee of 80% output for a long period of time at least for 25 years so that it can be compatible with the silicon solar cell efficiency.

So, there is a room for development is there and so we are going in the right direction, so we have seen that efficiency revolutions of a perovskite solar cell, starting from 4% we have able to reach to 23%. Silicon solar cell is already given 15 to 20%, so a conjugation of a silicon and perovskite can easily bring the technology to 35% or even more than 30% if so many other factors are optimized.

And at the same time, not only the efficiency, we have to look also for the production cost and also the stability of the devices. So, we hope that very soon it is possible to bring a technology where we can make a perovskite silicon tandem solar cell with the ultra-low cost and very highly stable module that can overcome any existing solar module. Thank you so much.