Solar Photovoltaics: Principles, Technologies and Materials
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Lecture – 26
Solar Cell Device Parameters

So, welcome again to the new lecture of Solar Photovoltaics: Principles, Technologies, and Materials. So, in the last lecture we started talking about the solar cell device parameters. We will further develop on that perhaps this is the last lecture on this topic before we move on to the technology. So, I will just do a brief recap first.

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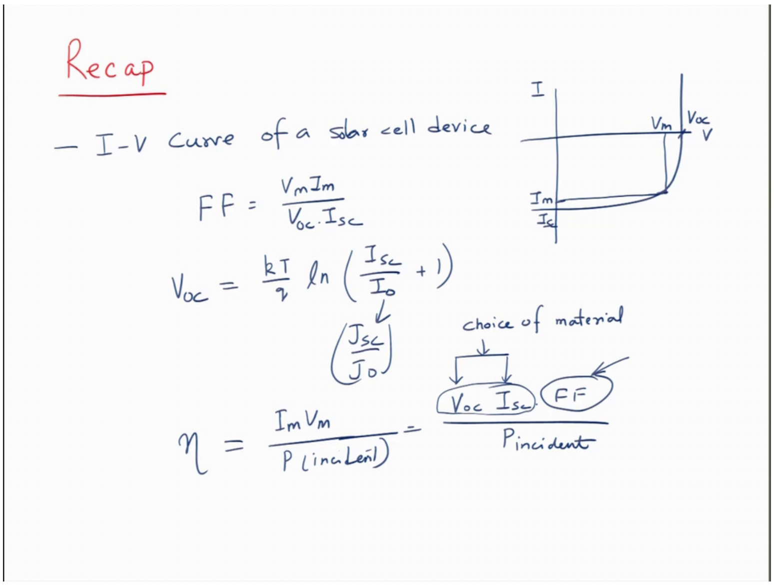

Recap

— I-V Curve of a solar cell device

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

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_{sc}}{I_o} + 1\right)$$

$$\downarrow \left(\frac{J_{sc}}{J_o}\right)$$

choice of material

$$\eta = \frac{I_m V_m}{P(\text{incident})} = \frac{\boxed{V_{oc}\ I_{sc}}\ \boxed{FF}}{P_{incident}}$$

So, what we saw in the last class was: what was the I-V curve of a solar cell solar cell device, which is typically a fourth quadrant curve figure a I-V curve like this. The important parameters are I sc, which is short circuit current; V oc which is the open circuit current at which the current is equal to 0 and I sc is the current at which voltage is equal to 0.

And the important thing about this was that the maximum the area; the rectangle of maximum area that can be drawn inside the curve determines the maximum power that you can drawn drop out of it. So, correspondingly you have currents and voltages I m and V m. And the ratio of these gives rise to what we call as fill factor which is V m I m divided by V oc into I sc.

Another parameter of importance is V oc here. And V oc is nothing but k T by q into ln of J sc divided by I sc divided by I naught you can say plus 1. So, I sc divided by I naught sorry, this should be like this yeah. It would be ln of I sc divided by I naught plus 1; you can also write this as J sc divided by J naught, because areas will cancel each other. So, this is ok.

And then we looked at the efficiency, that is power conversion efficiency which is I m V m divided by P incident energy, and this would be equal to V oc I sc into fill factor divided by P incident,.

So, the idea for a device engineer is to maximize their fill factor, I sc and V oc are going to be determined by choice of materials. So, once you choose a particular material there will only a extent to which I sc and V oc can be increased, you cannot obtain a; because V oc is determined by the bandgap of the material and I sc is also determined by how much a material can produce in terms of current.

So, both of these parameters are fixed maximum limit is fixed for given material. This can be up to 100 percent and that its seldom 100 percent, but most of the times its between the range 60 to 80 percent. And as a device engineer our job is to maximize this fill factor; and that will. So, if we can maximize by changing materials V oc and I sc and maximize the fill factor by device engineering you will obtain high efficiency in the devices.

Now what leads to maximization of these parameters in these devices, let us see that.

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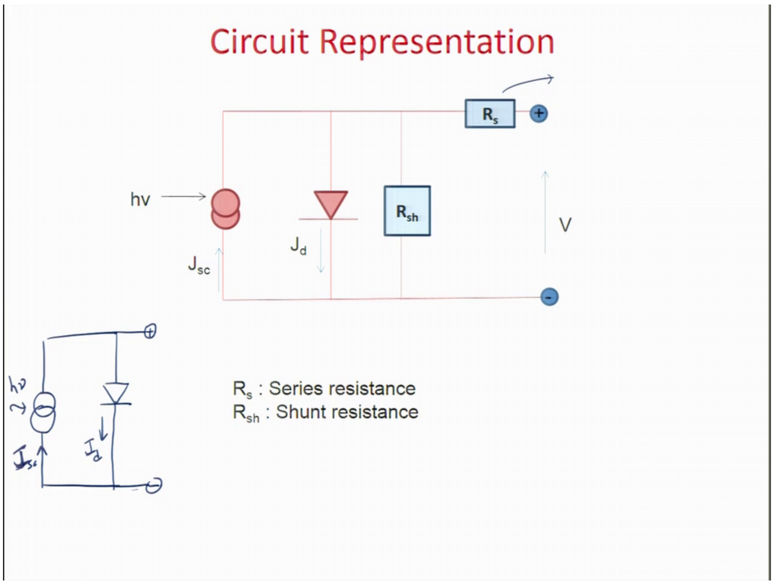
Circuit Representation

R_s : Series resistance
R_{sh} : Shunt resistance

So, solar cells are often represented by a electrical circuit. A ideal solar cell would be where there is no parasitic resistance. So, ideal solar cell would be drawn something like this. This would be your ideal solar cells, you have radiation coming, you give rise to a J sc or I sc. This would be a dark current that two opposing currents and there are no parasitic resistances.

So, the only thing that counters I d; I sc is the I d as a function of bias. Whereas, in reality a solar cell has parasitic resistances and these resistances are called as series and shunt resistance. So, series resistance is the one which is basically due to resistance in the device ok. So, your then the semiconductor can have high resistivity, which will create resistance to the path of electrons. Shunt resistance on the other hand corresponds to mechanism which leads to leakage of charge. The electrons and holes on the way they gets leaked out or they get lost in some other processes. So, this is represented by what we call as shunt resistance.

So, these two parameters are of extreme importance in solar cells, ok. We will see the effect of these two in case of solar cell devices. So, we look at the effect of these resistances on the performance of.

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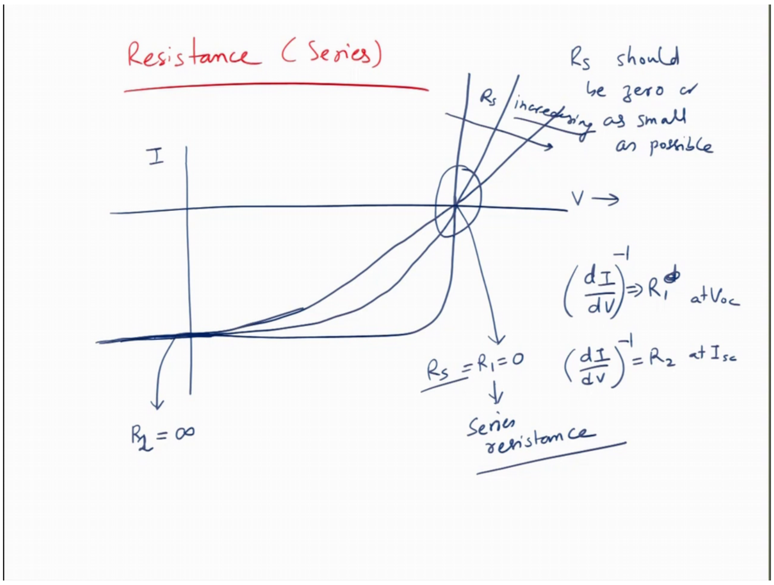

So, we first we look at the series resistance. So, when you look at the series resistance effect: the series resistance basically affects if you plot I-V characteristics of a solar cell. This is I, this is V, the series resistance tends to affect the so, for a good device series resistance should be 0, or as small as possible, right, whereas shunt resistance on the other hand should be as large as possible, so that you have minimum leakages. These are two basic concepts.

So, now, series resistance from this is going to be worked out from the slope of this plot. So, slope of this plot of course you can see you have two points, this point gives you a slope d I by d V, inverse of this is. So, inverse of this is the one resistance R n R 1. Again at this point you have, so this is at V oc. Now d I by d V inverse is equal to R 2 at I sc.

So, you can see that as we have said that our ideal curve should be as squarish as possible which means, the current should be nearly flat at I sc and voltage variation should be nearly vertical at I s at V oc. So, if you look at the slope at this point what is d I by d V at this point: d I by d V is equal to 0 at this point. So, which means R 1 is infinity at this point what is so sorry; R 2 is infinity this is R 2.

At this point I am saying that this line should be vertical, as vertical as possible. If this line is nearly if this line is 100 percent vertical then the slope at this point will be equal to infinity, which means R 1 will be equal to 0. So thus, the slope corresponding to this point that depicts what we call as series resistance. The series resistance for a ideal device should be equal to 0.

So, as the device performance changes, when the series resistance changes let us say if you have series resistance alone that changes then the behavior is like this, ok. And this direction would mean that your series resistance is increasing, alright; series resistance is increasing. At this point when the when it is vertical R 1 is equal to 0 which is equal to R s actually ok. Series it will increase because the slope is slope is; so this slope is infinity this slope is becoming at this point it is at this point we are saying that R 1 is equal to 0; R 1 is equal to 0 you are taking inverse right. So, the slope is decreasing which means the resistance is increasing alright.

So, this is the effect of increasing series resistance. If you want to look at the effect of increasing shunt resistance.

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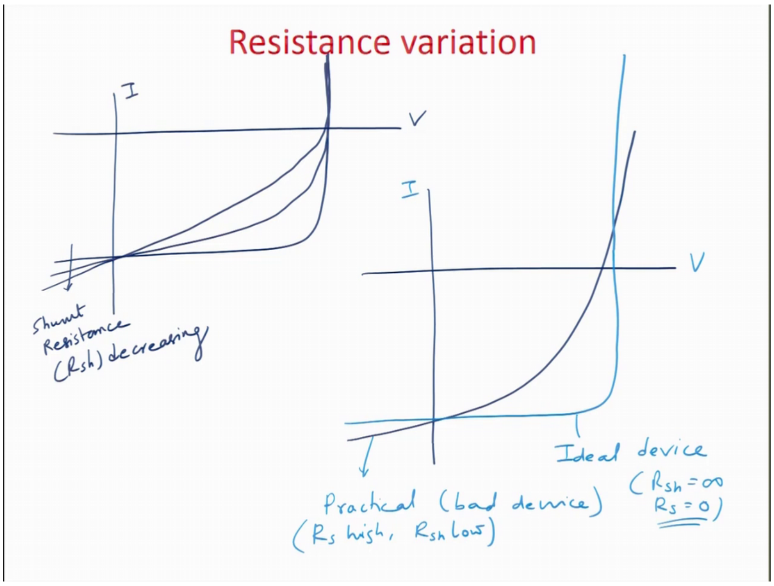

Resistance variation

So, the shunt resistance will go in the other way round. So, this is the ideal I-V curve you should have and the shunt resistance variation will be seen here. So, no change in series resistance, but you have change in the shunt resistance. So, this is shunt resistance R sh decreasing, because here the slope is increasing alright.

So, this is what is the effect of; and together what they will do is that generally you will see both series and shunt are series never equal to 0, shunt is never equal to infinity. So, in reality what happens is something like this. So, you will have; so this is the ideal one. So the ideal one is something like this ok. That the V oc may also change actually, this is ideal one and this is the practical one or rather back device actually I V.

So, for this R sh is equal to infinity and R s is equal to 0. For this R s high and R sh low. So, our job as a device engineer and materials engineer is to decrease the series resistance to 0 and increase the shunt resistance to infinity. So, that we get a good I-V behavior from these solar cells.

So, now if you want to plot the, if you want to do the power analysis the solar cell.

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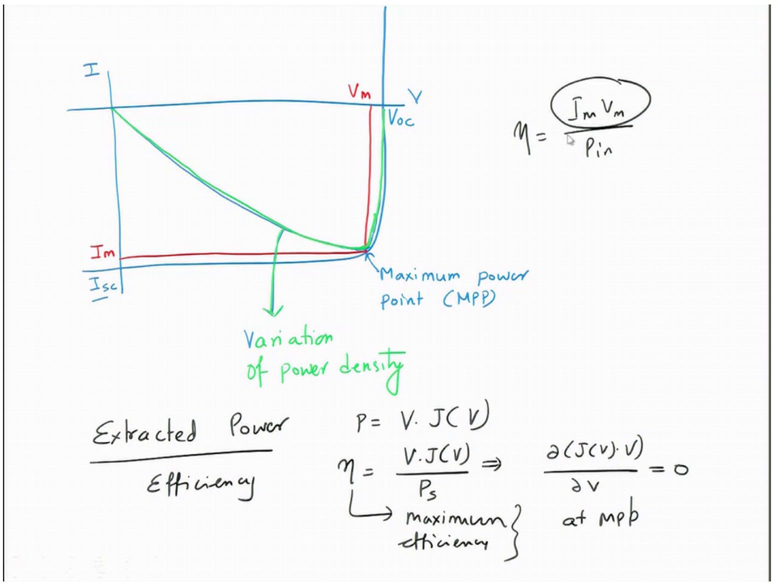

So, if for a solar cell the I-V curve is like this. This is I-V and within this we say that we can draw a rectangle whose. So, this is we can say I m, this is V m, correspondingly we have V oc and I sc. So, it is at this point the if you now plot; so this point we are saying is the maximum power point or MPP,. And the power if you now plot the power will go as; it will reach a maximum at this point before it goes decreases again.

So, this would be the variation of; I can use different color perhaps maybe the green one; this power will show a maxima at this point before it decreases. So, this would be the variation of power density on the solar cell which will achieve a maximum at the MPP point. So, the extracted power of a solar cell is equal to P is equal to V into J V. And efficiency is equal to V into J V divided by P s. And this is maximized when d of J V into V versus d V is equal to 0 right because it show a maxima here.

So, when you make the derivative of power with respect to voltage that should be 0. So, this is at MPP, and this is where you achieve the maximum efficiency or limiting efficiency which corresponds to the MPP. So, this is how these two are going to vary. So, your efficiency will also follow the similar kind of curve at this point. So, your efficiency will be maximum at corresponding to this point. So, essentially the idea is that is what we said I m V m divided by P in. And the idea is to increase this product of I m and V m in the solar cell device.

Now let us see a couple of more things relevant to the solar cells that is.

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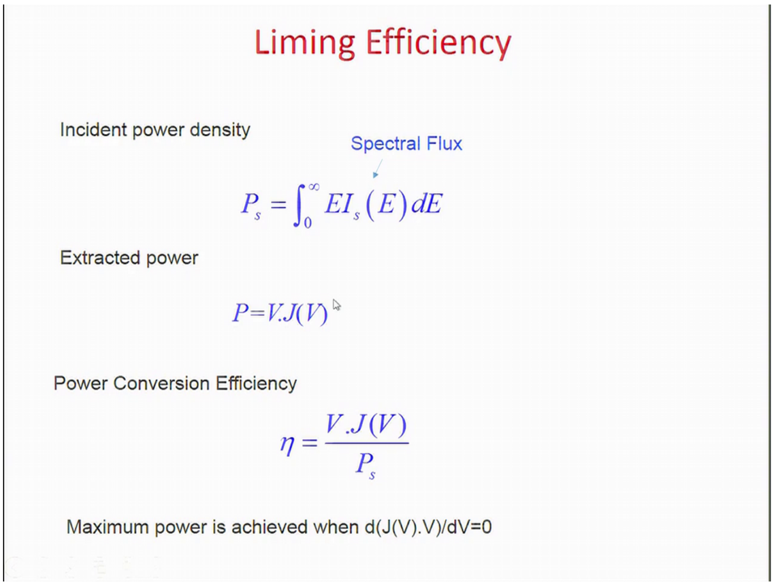

Liming Efficiency

Incident power density

Spectral Flux

$$P_s = \int_0^\infty E I_s(E)\, dE$$

Extracted power

$$P=V.J(V)$$

Power Conversion Efficiency

$$\eta = \frac{V.J(V)}{P_s}$$

Maximum power is achieved when d(J(V).V)/dV=0

This is what is we did here.

So, in incidents spectral in power density is this E into I s dE, and extracted power is V into J V or I-V if we take the area into consideration. And then power conversion efficiency is V into J V divided by P s. So, you need to worried about we need to take it take into account J and I’s carefully. So, J is current density I is current. And these two are loosely used in the literature, but make sure as a as a person who analyses the efficiencies they he or she must consider a areas carefully and get the unit slight.

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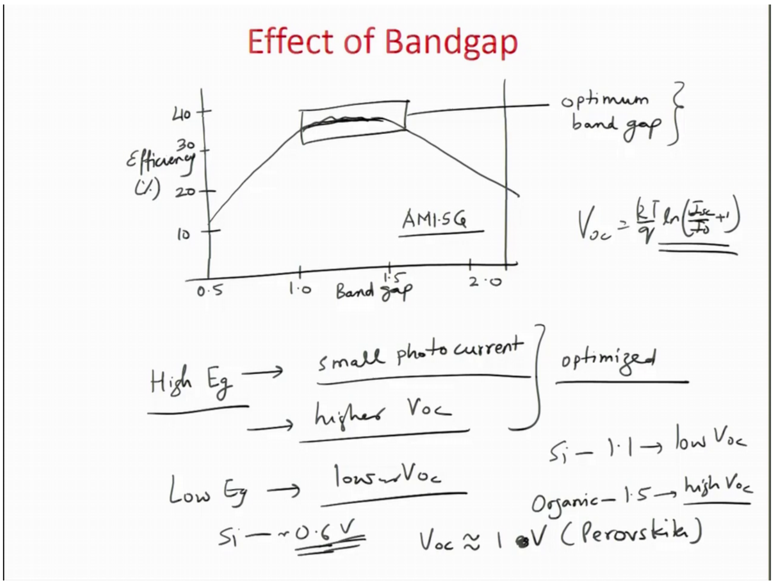

Effect of Bandgap

$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_{sc}}{I_0} + 1\right)$

High Eg → small photo current
→ higher Voc
optimized

Low Eg → lower Voc

Si — ~0.6 V

Si – 1.1 → low Voc

Organic – 1.5 → high Voc

Voc ≈ 1 V (Perovskite)

So now, we look at the effect of bandgap; efficiency versus bandgap of semiconductor. And theoretical calculation suggests that if you plot this efficiency at 10, 20, 30, 40. So, the system this is in percentage 10, 20, 30, 40, and let us say bandgap starting from 0.5, 1.0, 1.5, 2.0 and so on and so forth. So, the maxima in the efficiency is achieved at around these volt these points. And something like this, its not exactly flat it has some sort of replica kind of behavior and then it goes to nearly so. So within this range of 1 to 1.5 are these are the you can say the optimum bandgaps. Of course, there is a whole thermo dynamical analysis behind it and you can do to find out the exact bandgap. And this is that AM 1.5 G; that is 1 sum ok.

So, basically we see the corundum higher energy gap on one hand gives you small photocurrent, because you are going to absorb less number of photons, right. So, if your bandgap is higher the current is going to be smaller. But at the same time the V oc is higher, it also gives rise to higher V oc. So, these two things have to be optimized to get the maximum power output from the solar cell.

So, on the other hand you can see the low E g gives rise to lower V oc. So, lower working voltage is obtained for lower E g and higher E g will give you higher voltages. So, you will see for example, silicon which has a bandgap of 1.1 volt it will give you lower V oc. But somewhere something like you know perovskite or organic where the bandgap could be 1.5 or even higher they will give you higher V oc. So, for example, in perovskites we get a V oc of V oc of the order of 1 volt. So, this is for perovskites right whereas, for silicon we get V oc of nearly 0.6 approximately volt.

So, there is a huge difference between the open circuit voltages. And of course, but open circuit voltage is also a function of J sc. So, you can see that this is I sc divided by I naught plus 1. However, this since the relationship is logarithmic now increases not that rapid in V oc as a function of I sc. And so, the requirements that you want to have for an ideal solar cell device.

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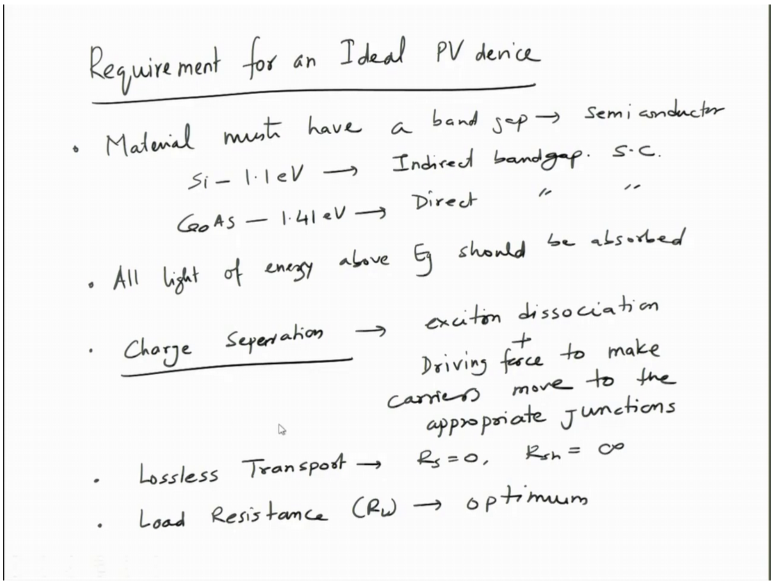

Requirement for an Ideal PV device

- Material must have a band gap → Semiconductor
  - Si – 1.1 eV → Indirect bandgap. S.C.
  - GaAs — 1.41 eV → Direct " "
- All light of energy above E_g should be absorbed
- Charge Seperation → exciton dissociation + Driving force to make carriers move to the appropriate Junctions
- Lossless Transport → $R_s = 0$, $R_{sh} = \infty$
- Load Resistance (R_L) → optimum

So, first is any material must have a must have a bandgap which means it must be a semiconductor. So, here silicon has a bandgap of 1.1 electron volt, silicone is a indirect bandgap semiconductor. Gallium arsenide on the other hand has a bandgap of 1.41 electron volt which is a direct bandgap semiconductor. So, gallium arsenide will give you higher V oc as compared to silicon. Second is all the light of energy above E g should be absorbed,.

And then charge separation. All the electron hole pairs they you create they must all get separated. So, basically you must have exciton dissociation, and then there must be a driving force in the device to make carriers move to the junction to the appropriate [FL]. And then there should be lost less transport, which means R s should be equal to 0 and R sh should be equal to infinity; that is what you want ok. And then the load resistance R l should be optimum; I mean the you cannot connect any obnoxiously high load to the solar cell it should be appropriately matched with the lower output of the solar cell device.

So, these are certain practical; a certain ideal certain requirements if you want to have a good device.

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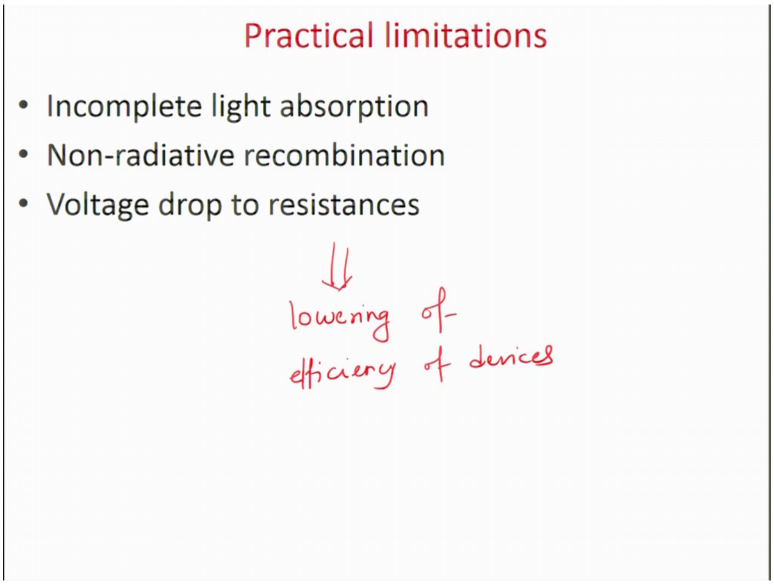

Practical limitations

- Incomplete light absorption
- Non-radiative recombination
- Voltage drop to resistances

⇓

lowering of

efficiency of devices

But there are some practical limitations as well. The devices have incomplete light absorption, there is a problem of non-radiative recombination, and there are voltage drop due to resistances you have shunt resistance you have series resistance which lead to voltage drop in the devices. And that is what causes lower efficiency of the devices all of these lead to lowering of efficiency of devices.

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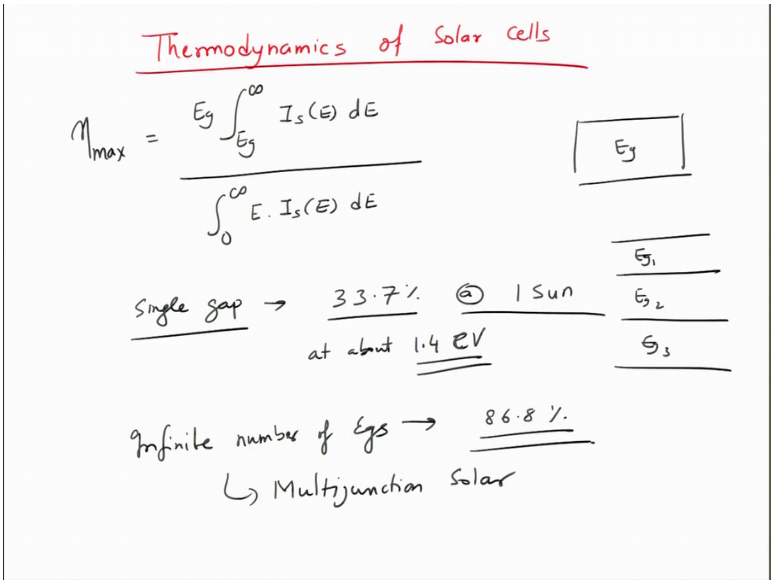

Thermodynamics of Solar Cells

$$\eta_{max} = \frac{E_g \int_{E_g}^{\infty} I_s(E)\, dE}{\int_0^{\infty} E . I_s(E)\, dE}$$

Single gap → 33.7% @ 1 sun

at about 1.4 eV

Infinite number of Egs → 86.8 %

↳ Multijunction Solar

So, generally if you would a one does the thermodynamic analysis of; we are not going to do this here because it is beyond the purview of this course. So, this leads to maximization of efficiency when eta max is; which means all the photons of energies above E g are absorbed. And if you do this analysis then maximum efficiency one obtains for single gap devices which means there is single semiconductor 33.7 percent at 1 shunt. And this bandgap is about at about 1.4 E V. So, this is the.

However, if you have infinite number of gaps which means you are able to use infinite number of materials with infinite number of gaps, which means you are able to absorb every wavelength that comes across because single gap is going to have a limit it is not going to be able to absorb anything below the bandgap. So, there is going to be cut off wavelength. But if you have luxury of having infinite number of gaps in a device then you can increase this efficiency to about 86.8 percent ok.

So, there is a possibility of having higher efficiency. So, this is the concept behind multijunction solar cells; since you can have. So, one solar cell will have only one, so this will have 1 E g, but you can have these multiple layers with different E g’s. So, that your E g 1 is E g 2, E g 3, so that you absorb the short wavelengths on the top lower wavelengths. So, short longer wavelengths at the make a device which is at multiple bandgaps which can give rise to higher efficiencies.

Of course, it is a design challenge for materials engineers, but theoretically speaking one can achieve efficiencies as high as 80 percent, 85 percent; if you are able to do good device engineering.

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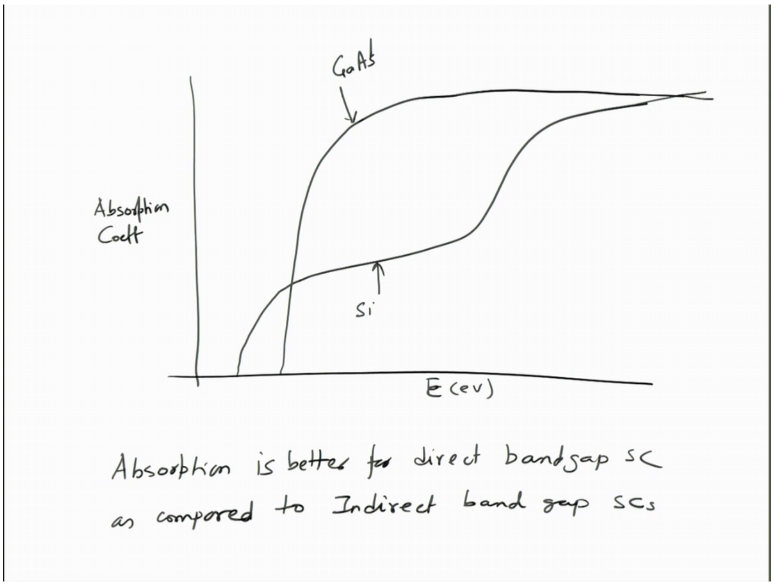

Absorption is better for direct bandgap SC
as compared to Indirect band gap SCs

And as far as I told you earlier also in the commercial semiconductors what is important the absorption coefficient. So, we plot the absorption coefficient as a function of energy. Silicon has a bandgap of 1.1. So, silicon is a indirect bandgap semiconductor it shows a behaviour something like this. Whereas, gallium arsenide has a bandgap of 1.41, this shows much higher absorption coefficient as compared to silicon.

So, this would be is something like gallium arsenide, and this would be silicon. So, generally absorption coefficients of; absorption is better for direct bandgap semiconductors as compared to bandgap semiconductors. So, this is in general possibility.

And if you just plot the efficiency somewhere as a function of bandgap this is what we have right now.

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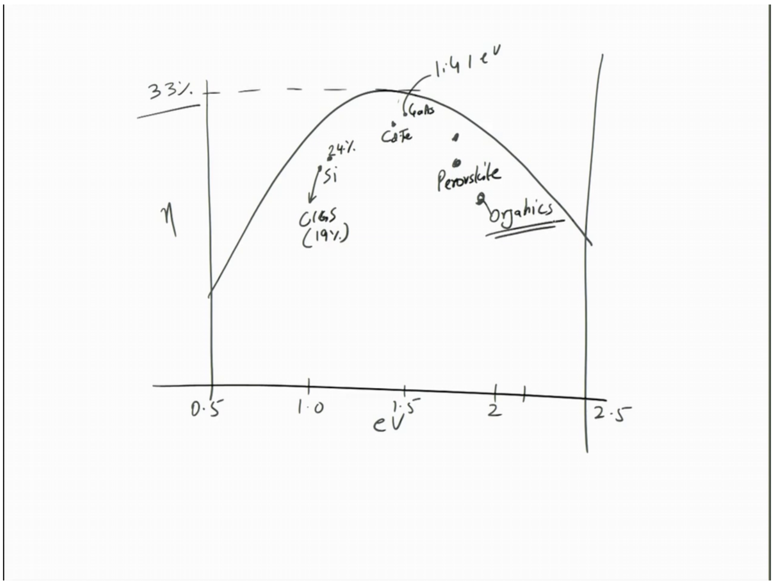

So, if you plot efficiency as a function of bandgap. So, I made the plot of E V versus eta it was something like that ok. And they shows a maxima at around 1.3-1.4 electron volt. So, your silicon is, so if let us say this is from 0.5 to or you know 2.5. So, this would be somewhere around; so this is for single junction devices about 33 percent.

So, your silicon is nowadays silicon is; so this is you know. So, about 1.5, 1, 2, 2, 1.5. So, silicon is somewhere here, this is silicon. Copper indium solenoid is somewhere, it is it is a little lower than silicon. So, somewhere here is silicon is right now we are at about 24 percent, 24.7 percent. This is CIGS which is at about 19 percent or so approximately. Cadmium telluride is little higher. So, cadmium telluride gallium arsenide will be somewhere here. So, this would be cadmium telluride, this would be gallium arsenide, gallium arsenide is that 1.41 E V catalyst the lower. And perovskites have already reached about 20 percent they have higher bandgap more than 1.5 E V.

So, perovskite are sitting somewhere here 20 percent or so somewhere here perovskites. And then we have organics: organics also ruffle in the same bandgap range lower efficiency is though. So, this is where we have organics. I will show you a chart later on in the next class which can give you a good idea about the devices.

So, this sort of complete completes our discussion on device parameters. We started with analysis of p-n junction in dark, then we look at p-n junction in light and then we looked at solar cell device parameter. The idea is to have a as square or rectangular I-V recover is possible with minimum parasitic resistances. And we have to optimize the bandgap to maximize the V oc.

So, we will stop here today.