

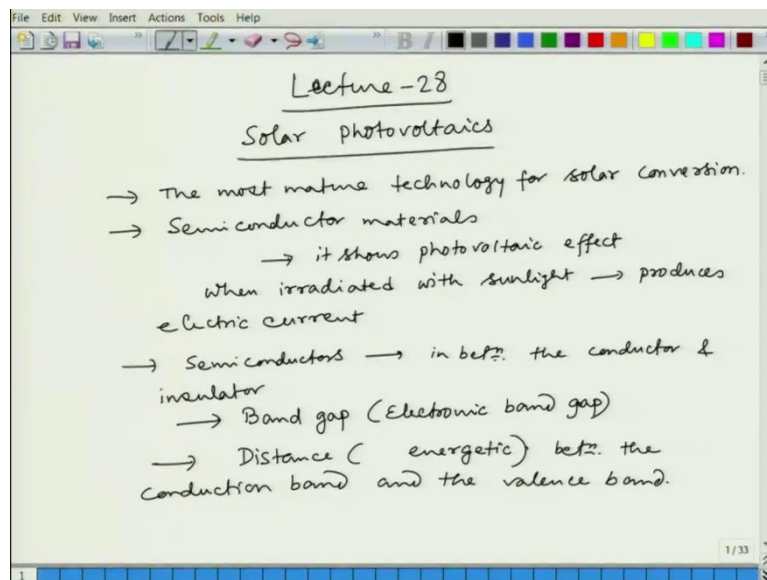
**Elements of Solar Energy Conversion**  
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**Lecture - 28**

Hello everybody. Welcome back to the series of lecture on Solar Energy Conversion. Today, we are going to start a different topic which is Solar Photovoltaics. Solar Photovoltaics is the most mature technology in terms of solar conversion today.

So, we have covered majorly two sections, where how the sun rays are available with us and how we can convert it through thermal route to useful energy; that is what we have considered so far. So, the last part of the course, we will focus on the solar photovoltaics.

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So, here, we are at lecture 28 and we are going to start solar photovoltaics. So, of course, with the remaining part of the course, there will be few lectures on which we will not be able to complete all the nitty gritty details of the solar photovoltaics, but you will be introduced to the major mechanism; how photovoltaics works and how you can design, or you can use a solar photovoltaic panel with understanding.

We will ensure that part, ok. So, it is the most mature technology for solar conversion, ok. The other thermal conversion they are maturing, people are looking at them. Now, most of them are still in research stage and solar photovoltaics also, is in research stage in terms of

developing new materials, more efficient materials and how we can improve the efficiency of the system, but ubiquitous you will see that there are lots of panels nowadays you will see on the rooftop, because the push that the whole world is going towards the renewable energy and that is why this mature technology solar photovoltaics is being used mostly. So, how does it work? You need some semiconductor material, ok. So, how does the semiconductor material help? It shows photovoltaic effect.

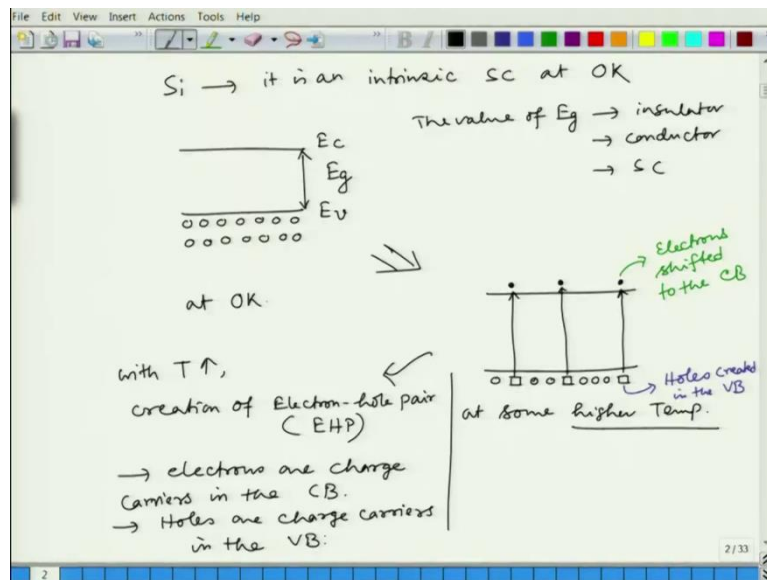
By the way, this photovoltaic effect was discovered by Sir Albert Einstein. This is one of the major success stories for his theory. So, this photovoltaic effect, what does it mean? It means that when irradiated with sunlight, it produces electric current, that is basically the photovoltaic effect means, ok.

So, the energy which is coming in the form of light and heat through the sunlight, it is getting converted into electrical current, ok. So, why these semiconductors are essential? So, basically these semiconductors, they are in between the conductor and insulator. Insulator which does not allow electricity to pass through it and conductor allows it very happily.

So, semiconductor it lies in between these two. And what property tells whether it is a conductor, semiconductor or insulator? It is the band gap or often called electronic band gap, ok. So, band gap is nothing, but the energetic distance between the conduction band and the valence band, ok.

How do they arise and all those things? You can look back at your high school textbook on physics or even your under-graduate electronics course. But what we will use? We will just recap those things, which are absolutely essential for this particular photovoltaic effect, ok.

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So, the example of a semiconductor material typically is silicon, ok. So, it is an intrinsic semiconductor. I will use acronym SC for semiconductor henceforth. And I should say at 0 K or 0 Kelvin temperature, absolute 0, because the band gap is a function of temperature also. So, we have to be careful about what temperature we are talking about.

Now, suppose, schematically we can show that the gap of bands in a material can be shown like this. So, this is what? This is the minimum energy of the conduction band and this is the maximum energy level for the valence band, ok. So, this gap is called the band gap or  $E_g$ , ok.

Now, depending on this  $E_g$ , the value of  $E_g$  tells us whether it is insulator, conductor or semiconductor, ok. So, now, what happens for this band gap? How the electrons are arranged on this? You can think of at 0 Kelvin, the electrons will all lie in the valence band only. There is no incentive for it to go up in the conduction band, ok. So, all the electrons are lying below the energy level of valence band.

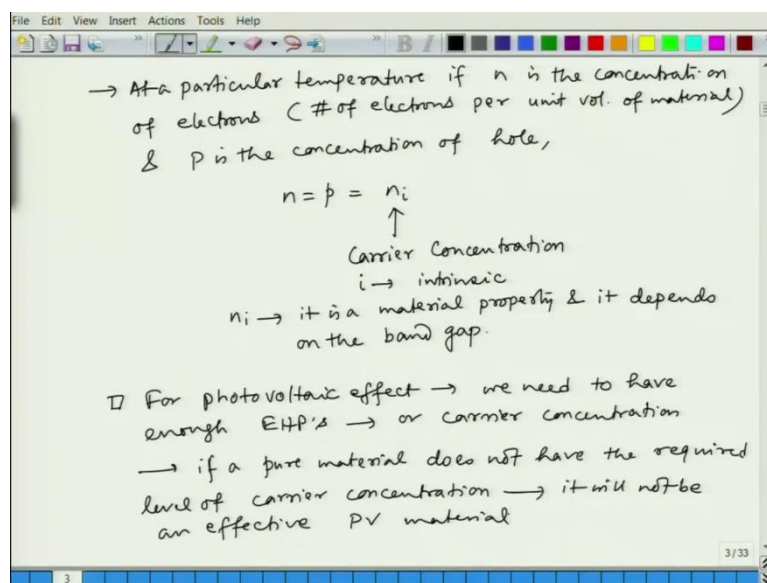
Now, this thing changes when you have certain higher temperature than 0 °C, ok. So, this is at some higher temperature. So, what happens? Few of these electrons jump to the conduction band, and they form these holes in the valence band, ok. So, again, let us say this electron jumped to the conduction band and then another electron jumped here.

So, how many electrons will jump from the valence band to the conduction band will depend on the temperature. So, this is at some higher temperature. What are these? These are the holes created in the valence band (VBs will stand for valence band).

And these are the electrons shifted to the conduction band, ok. When the electrons are in the conduction band, they will be able to act as charge carrier, they will be able to move around, ok. So, from here, what we get? With increase in temperature, we have creation of this electron hole-pair, ok. So, whenever a hole is created an electron is available in the conduction band, ok.

So, this is often abbreviated with EHP, which is electron hole pair. So, electron and hole will always exist in a pair form. So, a hole does not have any meaning without a counter part of an electron, ok. So, now, electrons are charge carriers in the conduction band right, because as you see here, the electrons are available in the conduction band. And similarly, holes are charge carriers in the valence band, is not it?

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So, what we can say that at a particular temperature, if  $n$  is the concentration of electrons. Concentration what do you mean? Number of electrons per unit volume of material, ok. So, it is basically volumetric concentration. So, if  $n$  is the concentration of electron and  $p$  is the concentration of hole then, what we can write,

$$n = p$$

Because electron and hole will always exist along with each other. So, one electron in the conduction band means, that there is a counter part of a hole in the valence band, ok. So,  $n$  will be equal to  $p$  and we can now write it as a common name which is  $n_i$ . We do not have to say whether it is electron concentration or hole concentration, but we can say it is carrier concentration  $n_i$ .

So, this is called carrier concentration. Both electron and hole they are charge carriers. So, this is called electron carrier concentration and  $i$  stands for intrinsic. Intrinsic means what? You will see in a short while that we can change this or we can tweak this carrier concentration by putting some other impurity or in the sense some other doping element in the original substrate element ok, we can change that.

So, intrinsic means when you do not have any impurity, it is pure material. In this case what we are looking at the example, we are using is silicon. So, for pure silicon bulk material, at any given temperature you will have certain carrier concentration, which is called intrinsic carrier concentration and we designate it with  $n_i$ , ok.

So,  $i$  stands for intrinsic. So, this  $n_i$  or intrinsic carrier concentration, it is a material property. What does it mean? You take silicon from Chile or silicon from Russia or silicon from Bangladesh, they will all have this particular value of intrinsic carrier concentration given a fixed temperature. It does not change with anything, it is a material property, ok. And it of course, depends on the band gap, ok.

So, band gap determines how many electrons will be able to jump from the valence band to the conduction band to create one electron hole pair and how many of those pairs will be created that will depend on the temperature and of course, the band gap, ok. So, this is called the intrinsic carrier concentration.

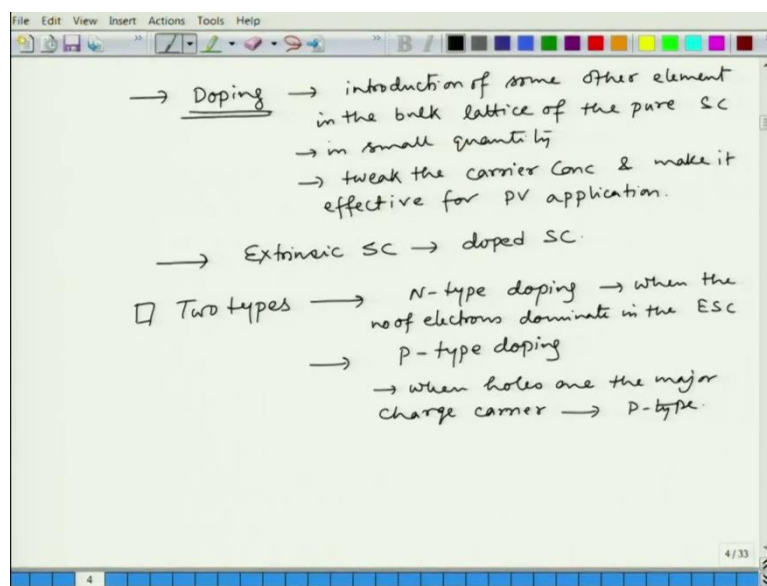
Now, for photovoltaic effect you can already assume that when you are putting some sunlight. So, you are basically putting in some energy in the material. So, in case of a semiconductor, that energy is being used to create this electron-hole pairs or to increase the carrier concentration.

Now, how much voltage you will generate or how much current you will generate that will depend on the carrier concentration that is available, ok. So, for photovoltaic effect, we need

to have enough this electron hole pairs or carrier concentration. If it is too low, it is of no use, ok. So, we need a minimum critical level above which we can use it effectively.

Now, a particular material may not have that intrinsic carrier concentration, right. So, if a pure material does not have the required level of carrier concentration, then it will not be an effective photovoltaic (PV) material. In that case, what we will need? We need to dope something. We have to introduce some other material which will introduce more carrier concentration or more electron-hole pairs.

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So, that is why we need to introduce doping, and doping means introduction of some other element in the bulk lattice of pure semiconductor and this introduction is in small quantity. You will see the numbers are really really small, but the effect can be tremendously high. And the reason for doing this is to tweak the carrier concentration value and make it effective for photovoltaic application, ok. So, that is the part of it.

And whenever we have introduced doping, we cannot call it intrinsic anymore. We will have to use another term which is called extrinsic. So, that is called extrinsic semiconductor or doped semiconductor, ok. Now, there can be two types of doping which is called either n-type doping or it can be p-type doping.

When we call it n-type doping? When the number of electrons dominate in this extrinsic semiconductor, then we call it n-type doping and when holes are the major charge carrier, we

call it p-type doping, ok. So, that is the difference and how we can make it? So far what we discussed that every electron will have a counter part of one hole.

Now, how can we increase the number of electrons than the holes? That is the part where doping is introduced. With some pure material you cannot do that, ok. So, that is why doping is introduced and let me explain this with certain examples, ok. So, we were talking about the intrinsic semiconductor silicon and silicon is in the periodic table.

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□ Si → column IV element  
if the impurity (dopant) is from III elements  
(B, Al, Ga, In) → additional energy levels  
for the neighboring Si — valence bands are created  
→ we call this new band/level → acceptor level.

————— VB

..... AB

..... VB

as III-column elements accept electrons and thereby  
produces additional holes for the Si-lattice → they  
are called acceptor dopant / acceptor impurities.

It is column four element, ok. Now, if the impurity or called dopant that we introduce in this intrinsic semiconductor silicon is from group III element or column III element, such as boron, aluminum, gallium, indium, etc. If dopant is from this then what we introduce? We introduce some additional energy levels for the neighboring silicon, ok.

So, basically, in a lattice of silicon you are introducing impurity. You can think of a sea of silicon where there are few impurity elements dispersed from each other, ok. So, around that particular impurity and whenever you have a lattice, the electrons are not bound to a particular lattice point or a particular nucleus. They are itinerant electrons and that is why, the impurity even if it is very small quantity, it can affect the whole band structure.

So, what does it do? This column III elements; they introduce additional energy levels for the neighboring silicon atoms, ok. So, what does it do? The valence bands are created. So, basically, the material does not know what is a valence band or what is a conduction band?

We name them for our own ease of talking ok or leveling so that we can communicate among ourselves.

So, what does these elements do? They create an energy level which is close to the original valence band of silicon and that is why we call that they create a valence band. And we call this new band or new level to be acceptor level. Let me explain, why we call it acceptor level, ok. So, suppose, this is the intrinsic band structure for silicon, this is the conduction band and this is the valence band.

Now, suppose you are doping it with aluminum? So, what it does. It creates an energy level which is close to the valence band, ok. So, what it does? So, now, this band gap is small. So, electrons even with small energy input, it can jump to this particular band, acceptor level, ok.

Let us say this is the acceptor band, ok. So, now, the electrons with small energy they can jump and create a hole here, ok. So, few of the electrons can create electron hole pairs others they do not, depending on the available energy. So, what are they doing and in the lower level of course, all the electrons are there; they are not being able to jump. Jumping will always happen from the edge of the band, because they have the maximum energy. So, little push will let them to the next level, ok.

So, what are this acceptor band? So, acceptor band why we call it? Because it can accept electrons from the original valence band; that is why we are calling it acceptor band. So, as this third column elements accepts electrons and thereby produces additional holes for the silicon lattice, they are called acceptor dopant or acceptor impurities, ok.



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Ex At room temp  $n_{i, Si} = 1.5 \times 10^{10} \text{ cm}^{-3}$   
 If it is doped with  $1 \times 10^{15}$  atoms of Al /  $\text{cm}^{-3}$   
 → At room temp, all the Al atoms will ionize  
 to produce the same no. of holes →  
 $\Rightarrow n_{i, Si} = n_e = 1.5 \times 10^{10} \text{ cm}^{-3}$   
 additional holes,  $\Delta n_p = 1 \times 10^{15} \text{ cm}^{-3}$   
 $n_{e, \text{extrinsic}} = 1.5 \times 10^{10}$   
 $n_{p, \text{extrinsic}} = (1.5 \times 10^{10} + 1 \times 10^{15}) \text{ cm}^{-3}$   
 $n_{p, \text{extrinsic}} \gg n_{e, \text{extrinsic}}$   
 $\Rightarrow$  p-type SC → holes are dominating.

Now, let us take an example of how this small amount of impurity can change the carrier concentration? ok. So, let us take a small example that at room temperature, the intrinsic carrier concentration for silicon is this value and I told you that this is a material property. So, per centimeter cube of pure silicon you will have  $1.5 \times 10^{10}$  electrons and equal number of holes, ok.

Now, if it is doped with  $1 \times 10^{15}$  atoms of aluminum per cubic centimeter, ok. So, room temperature is high enough for most of these atomic level energy hopping and all. Because room temperature is basically 273 K, ok. So, at room temperature, all the aluminum atoms will ionize, that means, all of them will contribute to the electron acceptor level to produce the same number of holes, ok.

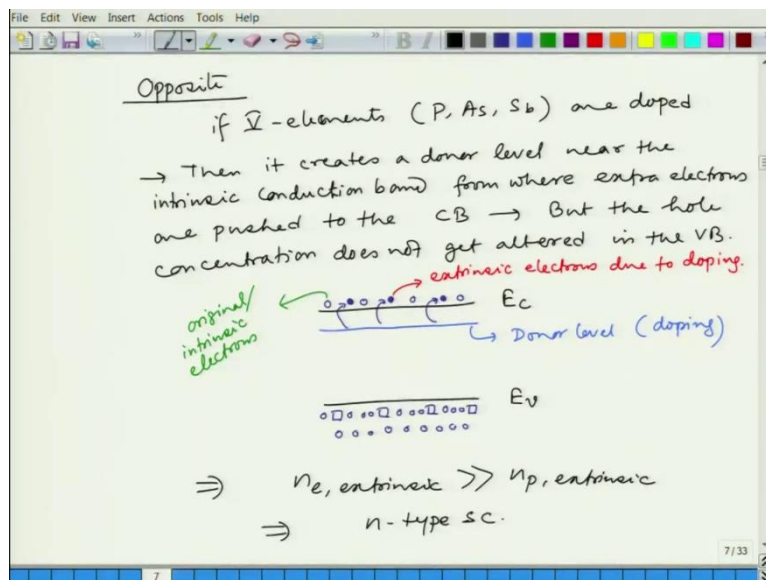
So, we have seen that each electron that the aluminum will accept will create a corresponding hole in the valence band of pure silicon, ok. So, what we can see here, that the  $n_{i, Si}$  is equal to number of electrons in the conduction band right and that was  $1.5 \times 10^{10}$  per cubic centimeter.

Now, additional holes that we have in the valence band,  $\Delta n_p = 1 \times 10^{15}$  per centimeter cube right, because each aluminum atom will introduce one hole in the valence band, ok. So, you can now see that  $n_{e, \text{extrinsic}}$  (number of electrons for the extrinsic semiconductor) will remain the same right, because in the acceptor level, electrons they do not count; they are not contributing to the conduction band carrier concentration, ok.

So, they remain the same, but for the holes what we have extrinsic hole concentration is now  $(1.5 \times 10^{10} + 1 \times 10^{15})$ . So, you can see that this extrinsic hole concentration is greater than the extrinsic electron concentration. So, can you see that how dominant a small quantity. So,  $1 \times 10^{15}$  atoms per centimeter cube is nothing right, because the Avogadro number is  $10^{23}$ .

So, we have very few atoms per the substrate silicon atom we are introducing, but the effect is huge, ok. So, that is why we called it is a p-type semiconductor, because the holes are dominating, ok. Now, what happens when we have the opposite kind of doping, ok. So, for the fifth column elements such as, phosphorus, arsenic, antimony, if these elements are doped.

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So, if these elements are doped then just the opposite happen. So, it creates a donor level donor level near the intrinsic conduction band from where extra electrons are pushed to the conduction band, but the hole concentration does not get altered in the valence band, right.

So, exactly opposite thing happens. Here, you have this intrinsic conduction level and valence level, ok. Now, what it does? This introduces a level. Some mezzanine level you can think of close to the conduction band which is called the donor level, and this is introduced due to doping.

Now, whenever you have that, what it does? Some electrons are pushed from here, and you have some extra electron from the donor level to the conduction level of the intrinsic material, but what you originally had, like if you say, that these are the original electrons. Only those counter parts will have some hole here, ok.

So, here we distinguish between these two. One is, these are original or intrinsic electrons, and these are extrinsic electrons due to doping, ok. So, as a result what we have? That electron concentration in the extrinsic semiconductor will be much much greater than the hole concentration in the extrinsic semiconductor, is not it?

So, that is how we will have n-type semiconductor. Whenever the electron concentration dominates, we will have n-type and whenever the hole concentration dominates, we will have p-type. So, that is how this doping can generate n-type and p-type semiconductors, ok.

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⇒ Need to quantify the additional extrinsic carrier concentrations.

→ √ ① density of states (DOS) — How many different options an electron has, which have a particular energy.  
 √ ② Fermi-function → how the energy states are distributed

① Density of States

$$g_c(E) = \frac{m_n^* \sqrt{2 m_n^* (E - E_c)}}{\pi^2 \hbar^3} \quad \text{for } E \geq E_c$$

cb. → Conduction Band.

$m_n^*$  → effective mass of electron.  
 Subscript n → electron.  
 " p → hole  
 $\hbar$  → modified Planck's constant

So, these are all good in terms of getting the concept, right. Why this is happening? Now, that is not enough to design something, right. So, we need to quantify the additional extrinsic carrier concentrations.

Now, whenever you go for quantification, you will have to look at the electronic structure, their exact energy and how that is getting changed when you introduce a dopant. So, all these quantum mechanical understanding of material in the smallest scale of the smallest length scale that is necessary. And of course, we cannot cover that in this course.

So, we will assume many things, if you are interested you can look back in the quantum mechanical route of those relationships and understand why those relationships are taking that particular form. Here, what we are going to do? We are going to use them, not derive them.

So, here, whenever you want to quantify, two things come into picture. One is called the density of states. Often, it is abbreviated as DOS, ok. Density of states means, at a particular energy level how many different electronic states are available. And the other thing is the Fermi-function, ok. Fermi-function is a function which tells us, how the energy states are distributed, ok, that is the Fermi-function which is named after Enrico Fermi the famous physicist.

And the density of states tells you how many different options an electron has while having a particular energy level. So, some electron has some energy, you know that. Now, there are many possibilities of states that the electron can have and for each energy level you will have multiple of them and how many of them are available is called density of state, ok. So, these two quantities will tell us exactly how the distribution will happen.

So, 1<sup>st</sup> thing we will look at the density of states  $[g_c(E)]$  and this density of state can be expressed very simply in terms of for the conduction band. Here, g stands for the density, c stands for conduction band and E is for that particular energy. We are talking about this, right. For a particular energy, how many states are available?

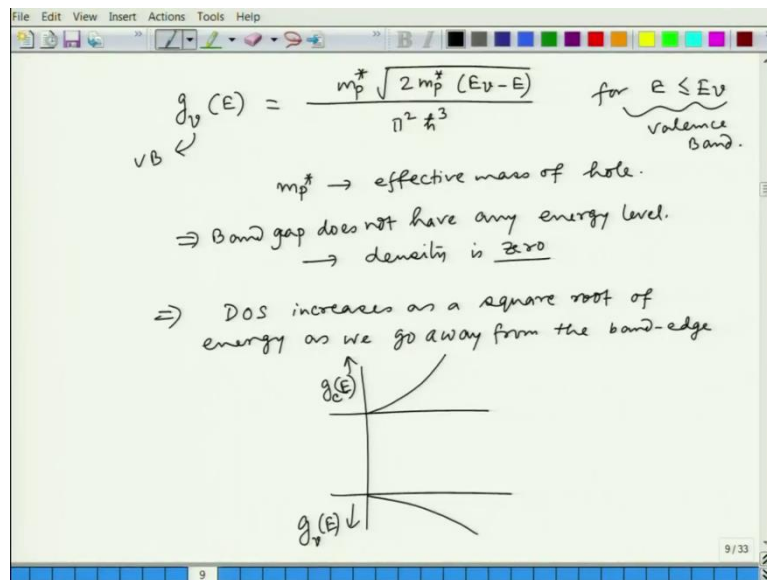
So, if you want to quantify that let me write it first.

$$[g_c(E)] = \frac{m_n^* \sqrt{2m_n^*(E-E_c)}}{\pi^2 \hbar^3} \quad \text{for } E \geq E_c$$

Now, here, this  $m_n^*$  is the effective mass or often called reduced mass of electron, whenever you have subscript n, it is for electron and subscript p is for hole ok; p for positive and it is hole and n for negative which is electron.

And what are the other things. Other things here,  $\pi$  you know it is the universal constant and this  $\hbar$  is your modified Planks constant. So, that is actually giving us the quantum mechanical information. So, whenever you have Plank constant h you will know that the origin of that expression is coming from quantum mechanics, ok. And  $\hbar$  means, the modified Planks constant.

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Now, similarly we can have the expression for the valence band, ok. So, this is for the valence band and what is the carrier constant or density of state there. We can write exactly similar expression, but now, we have it in terms of holes,

$$[g_v(E)] = \frac{m_p^* \sqrt{2m_p^* (E_v - E)}}{\pi^2 \hbar^3} \quad \text{for } E \leq E_c$$

It means we are in the valence band and  $m_p^*$  is the effective mass of hole. So, here, you can see that of course, in the band gap there will be no density of state right, nothing will be available and that is why it is called band gap. No state is available in that energy level. So, what is the expression for that? So, let me write that also. Band gap does not have any energy level. So, that is why the density is 0 there right and both this expression are either for the conduction band or for the valence band.

So, also note here, that the density of state, it increases as a square root of energy as we go away from the band edge. For either valence band or conduction band, if you go away from the band then, the density is increasing. So, if we say this is the conduction band and this is the valence band and if you draw density from here. So, the density is increasing as you go away from the band edge and here also density is increasing.

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② Fermi-function (Fermi-Dirac Distribution)

→ It gives the probability that an available energy state at an energy level  $E$  will be occupied by an electron at absolute  $T$

$$f(E) = \frac{1}{1 + e^{(E-E_F)/KT}}$$

$E_F$  → Fermi level → when the probability is  $\frac{1}{2}$

$$E = E_F \Rightarrow f(E) = \frac{1}{2}$$

⇒ The distribution is symmetric around  $E_F$

→ Fermi function is valid only under equilibrium condition

→ whenever you have some sunlight or some voltage applied → the fermi function shifts.

So, this way the  $g_v(E)$  it is increasing and this way the  $g_c(E)$  is increasing and that relationship is varying with the square root of the difference in energy. Now, other than the density of state, we have the second quantity which is Fermi-function and it is also called Fermi-Dirac distribution.

So, the original statistical distribution was proposed by Fermi and Dirac together. And for this particular calculation or for band structure description, it was used by Fermi, so, that is why it is called Fermi-function. So, what does it give? It gives us the probability that an available energy state at an energy level  $E$ . So, for a particular energy level  $E$ , you can have multiple energy states which is given by the density of state, right.

So, what this one gives? It gives the probability that a particular energy state among many (which are available at energy level  $E$ ) will be occupied by an electron at absolute temperature, ok. So, it will be a function of temperature. Now, you can think of it, you can close your eyes and you can think of it for a particular energy level  $E$ , you can have several energy state possible. So, basically several ways of getting that particular  $E$  ok, and that is given by the density of state.

Now, Fermi-function is giving you the probability of those many electron states. Whether an electron will occupy that state or not is given by the Fermi-function, ok. And you know that in quantum mechanics, everything is probabilistic, right. So, we always talk about the probability of occupancy.

And what is the form of that function. So, for any given energy level, the Fermi function,

$$f(E) = \frac{1}{1 + e^{\frac{E-E_F}{kT}}}$$

And this  $E_F$  is called the Fermi level, which is basically defined when the probability is half, ok. So, basically  $E_F$  is nothing, but,

$$E = E_F \Rightarrow f(E) = \frac{1}{2}$$

Because the second term becomes 1 when you have  $E = E_F$ . So, that is how the Fermi level is defined and, ok.

So, with temperature the first thing you can see the distribution is symmetric around  $E_F$ . So, if you go above  $E_F$ , a certain distance in terms of energy you will have the same Fermi-function and if you go below the Fermi level by the same distance you will have the same Fermi-function. So, that is why it is symmetric, ok.

Now, this Fermi-function is valid only under equilibrium condition, ok. So, when there is nothing affecting, there is no energy source or sink which is affecting the band structure then the Fermi-function is applicable. So, whenever you have either some sunlight coming in or some voltage applied, then it is no longer in equilibrium state and there the Fermi-function is shifted, it is not changed, but it is shifted from the Fermi level. So, the Fermi-function shifts. And these two quantities will tell us how the band structure will be affected for the doped semiconductors and we will see this in the next class.

Thank you very much.