Physics of Renewable Energy Systems
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Lecture 06
Basics of Semiconductors

Welcome again to this course on physics of renewable energy systems and till now, we have given you a brief introduction about the course, the basic need for energy systems, what are the various energy sources which we are going to discuss in this course, then we have moved our focus on solar radiations and then how solar radiations can be used to make solar based devices.

When we started discussing about the solar based devices, we saw that it is essential to understand the materials and more so the materials which had semiconducting properties, and therefore, in today's lecture, we will try to give you the basics of semiconductors and the properties of semiconductors, which would be useful for us during this course.

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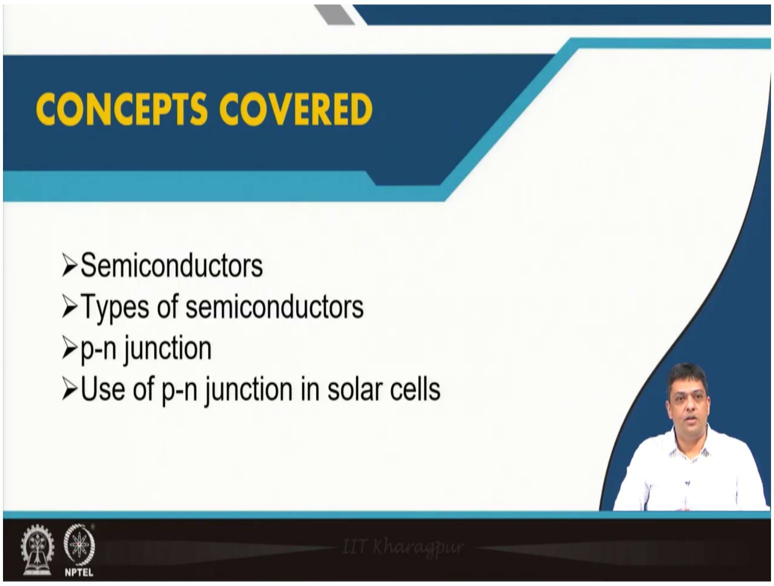

So, in today's lecture will give you the basics on semiconductors the p-type semiconductors, what are n-type semiconductors and how do we form the p-n junction and once this p-n junction diode is formed, can we use a similar system or a device in fabricating solar cells.

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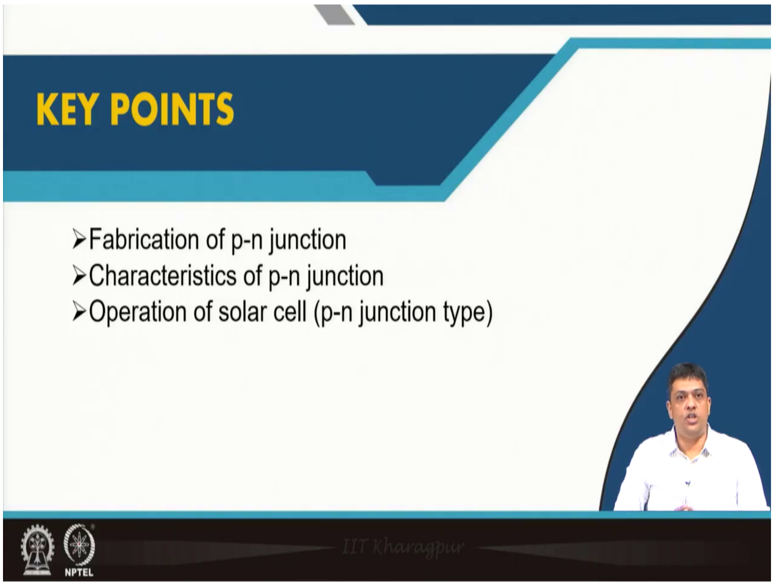

The most important points which we would be covering and you would be understanding today would be the fabrication of a p-n junction characterization of a p-n junction or characteristics of a p-n junction and then how this p-n junction was used to fabricate a solar cell.

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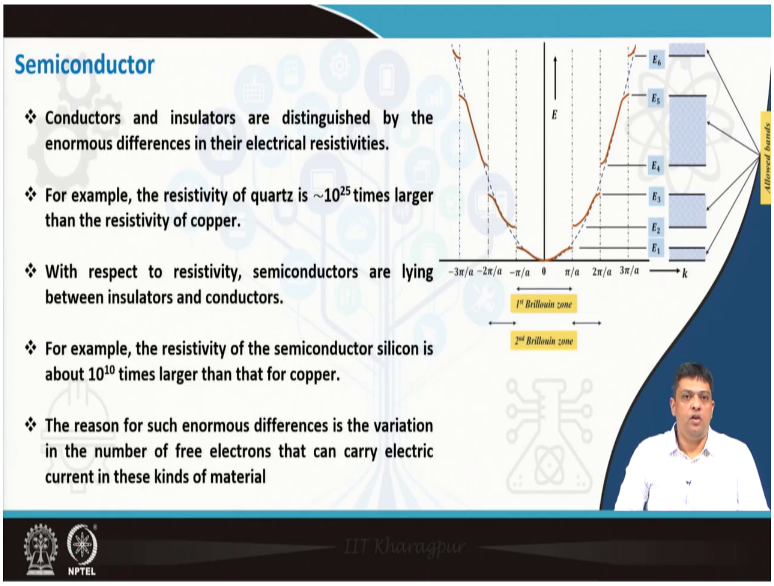

In the previous class, we saw that using the free electron model, we could actually explain the origin of band gap in solids and depending upon the magnitude of this band gap, we could differentiate insulators and semiconductors, whereas in metals the valence band and the conduction band was overlapping, so we had seen this in the previous case and in terms of resistivity we already know from our school days that semiconductors are the ones which lie between insulators and conductors.

For example, the resistivity of a semi conducting silicon is about 10 raise to or 10 times larger than that of copper. The reasons for such enormous difference is the variation in the number of free electrons that can carry electric current in these kinds of materials. So, this is what we have either understood in the previous lecture or from our knowledge from schools or bachelor levels.

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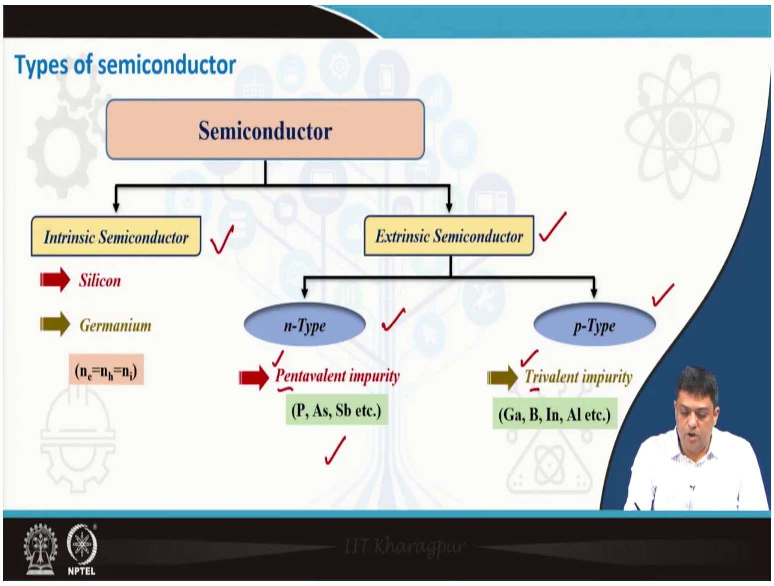

So, the types of semiconductors are basically intrinsic type semiconductors or extrinsic type semiconductors. In intrinsic type semiconductors, you have the number of electrons or number of holes are equal whereas, in extrinsic semiconductors, there are two types the n-type or the p-type, where in n-types semiconductors the majority charge carriers are electrons whereas, the p-type semiconductors have holes as the majority charge carriers.

And these n-type semiconductors are formed by doping there with Pentavalent impurities that means, they can donate one extra electron and the p-type semiconductors are formed by using trivalent impurities that means effectively they leave behind a positive charge so, that is hole.

So, depending upon the nature of the property of the impurities you can have the n-type or the p-type semiconductors.

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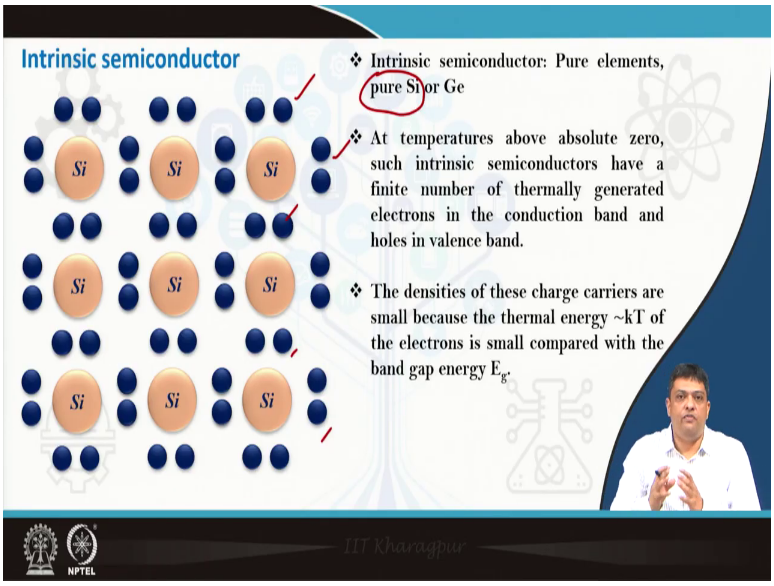

So, for intrinsic semiconductor if we take silicon for our discussion today then we have taken pure silica at temperatures above absolute zero such intrinsic semiconductors have a finite number of thermally generated electrons in the conduction band and holes in the valence band.

So, the electrons which you have, if you go above absolute zero then, because of the temperature you increase k beta T that is the thermal energy and then you have certain electrons which are generated in conduction band and they leave behind an effective charge in the valence band and the densities of these charges are small, because the thermal energy that is approximately kT of the electrons is still small compared to the band gap energy eg.

So why do we have less number of charge carriers because, charge carriers will become available when there is a jump from the valence band to the conduction band and these electrons become free, but because the band gap is much larger than the energy which is available for the excitation of these electrons, so the number of electrons which are actually able to jump from valence band to the conduction band remains low and therefore, the densities of these charge carriers are small.

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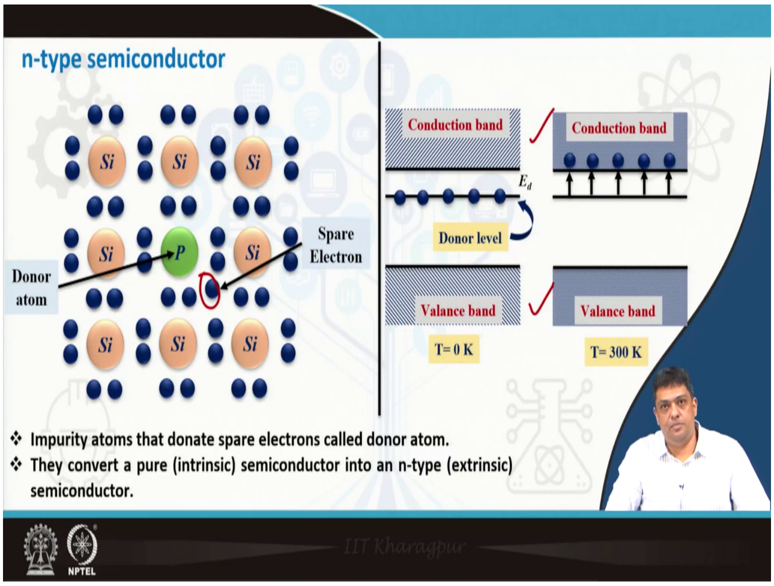

Now, we go to the extrinsic type semiconductors let us start with n-type semiconductor, so again let us take a silicon lattice and now, we dope it with a Pentavalent atom, let us say phosphorus and this will give you a spare electron this electron is now able to increase the conductivity in this kind of semiconductor.

So, impurity atoms in this case are the ones that donate their spare electrons which become available for conduction and such kind of impurity atoms are called as donor atom and these donor atoms convert a pure semiconductor also called as intrinsic semiconductor into an extrinsic semiconductor. In this case, we are talking about the formation of n-type semiconductor and what happens?

You have the valence band and the conduction band formation we know in semiconductors you have the valence band and the conduction band and the energy of the donor atom ensures that it is, if you are nearer to the conduction by then at T is equal to 0 the donor atom energy level is nearer to the conduction band now, what happens? I increase the temperature above absolute 0 and if that happens, what happens there are electrons from these donor atoms which are able to jump to the conduction band and then take part in the conduction mechanism.

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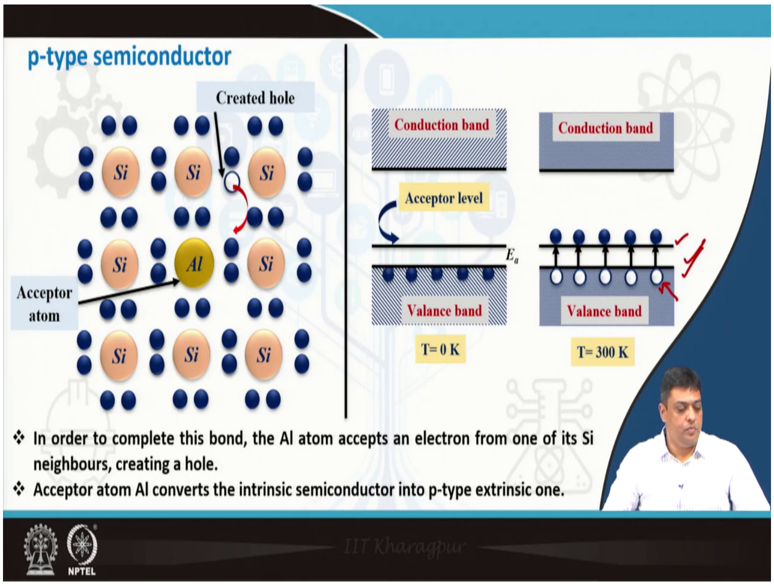

Similarly, you have p-type semiconductors just the opposite you have the atoms which are used to replace silicon here you are using a trivalent and atom and if you are using a trivalent atom, you just simulate it condition which is opposite to earlier case that, when the electrons from valence band is actually able to jump to the energy level in the acceptor atom, then they effectively leave behind a positive charge and that is called as hole and now hole transport takes here in the conduction mechanism in p-type semiconductors. So, we have two types of semiconductors p-type and n-type semiconductors, so these are the two types of semiconductors which are available to us.

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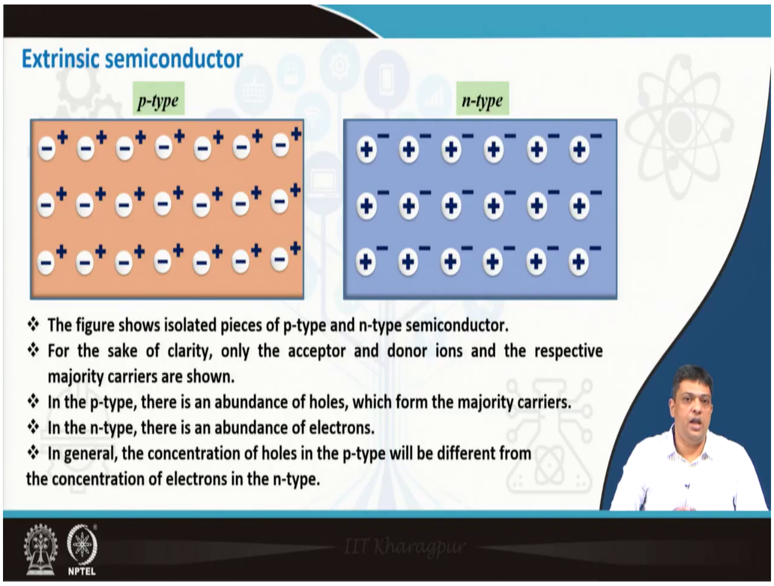

In this case, we have just shown you the acceptor and donor ions and the respective majority carriers are indicated. Once again, we should remember in p-type holes are the majority carriers whereas, n-type the electrons are the majority carriers and in general, the concentration of holes in p-type semiconductors will be different from the concentration of electrons in n-types semiconductors.

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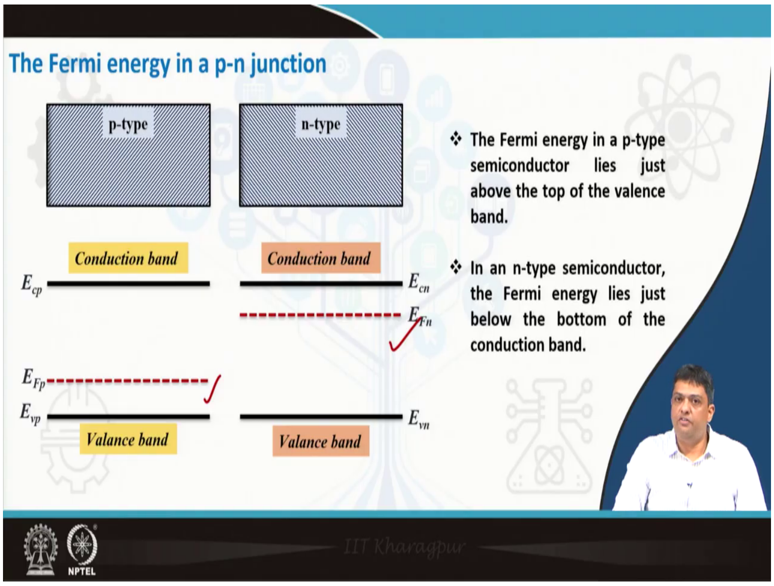

And in terms of Fermi level you will find if you have a p-type semiconductor then the Fermi level is nearer to the valence band and if you have n-type semiconductor the Fermi level is nearer to the conduction bands, so these are the explanation in terms of Fermi level.

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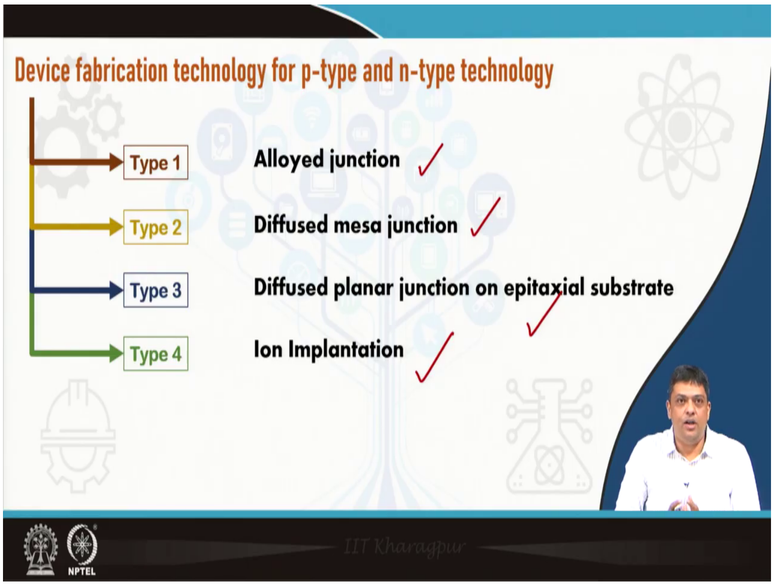

Now, many a times if you think over the semiconductor devices, you always get this question, how do we actually fabricate a p-n junction is it a physical formation do we bring two materials one n-type p-type and then physically a joint is made and then you get a junction or do have an atomic level doping which is taking place and then the junction is formed, this question is always going to be asked by an expert in an interview or by a person whom you may teach at a later stage and you will also be curious yourself to understand, what is happening.

and to make this p-n junction, there are various techniques that have been used they are Alloyed junction, the Diffused mesa junction or Diffused planar junction on epitaxial substrate or Ion implementation. So, these are the four common methods by which we tend to make p-n junction. Let us try to understand one by one what do we mean by these kinds of fabrications.

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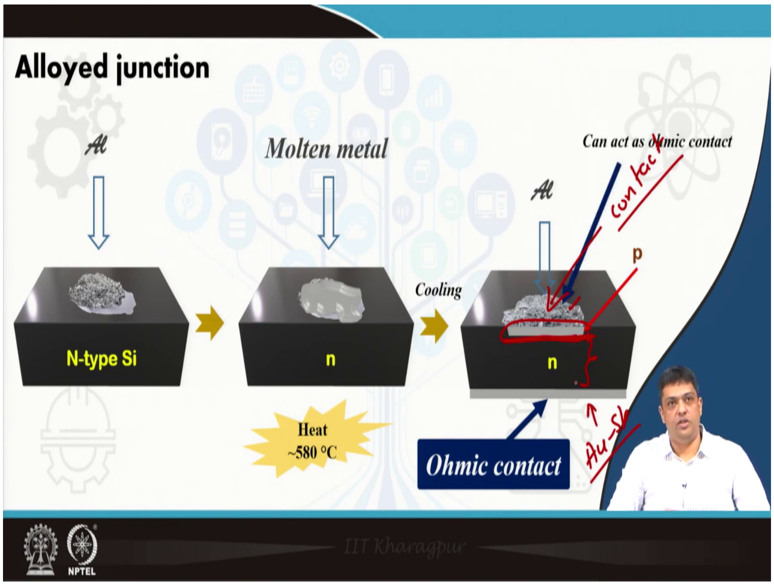

Let us take an Alloyed junction so, what do we do? We start with an n-type silicon, so we have an n-type silicon that is an extrinsic semiconductor on top of this n-type silicon, what do we want to make, we want to make up p junction, so what do we want to do we want to have a trivalent ion actually doping the system.

So what do we do, we drop aluminium on top of silicon and then you heat this aluminium which is on the n-type silicon above the eutectic temperature of 580 degrees C, this forms are silicon aluminium puddle you then allow this to cool down as it cools down, what happens?

When you are above the eutectic temperature you lead to the certain fraction of aluminium actually diffuses through the silicon surface and they lead to the growth of a p-type region just below the surface, so you have a p-type and then you have the n-type.

Now, aluminium on top of the surface is conducting, that can be when it cools down, this can actually be used as a contact, so you can use it as a contact, so this area is used as a contact whereas, the aluminium which diffuses in acts as a trivalent dopant and reach to the formation of a p-type layer in the n-type substrate and then you get a p-n junction which is form just here. So, this is one way of forming the p-n junction.

Now, to make a p-n junction diode you need another electrode that is current collector or conducting contact, so here you can use, let us say a dopant like gold antimony and that can lead to the formation of n plus area and that same process you make an gold antimony deposit heated and then let it cool and you will get a n plus region or along with that you will get Ohmic contact formed at the bottom of the surface, so you have bottom n-type formation of p-type layer because of diffusion and then, the formation of aluminium base contact. So, this is a typical method which was initially used to fabricate p-n junction and is called as an Alloyed junction.

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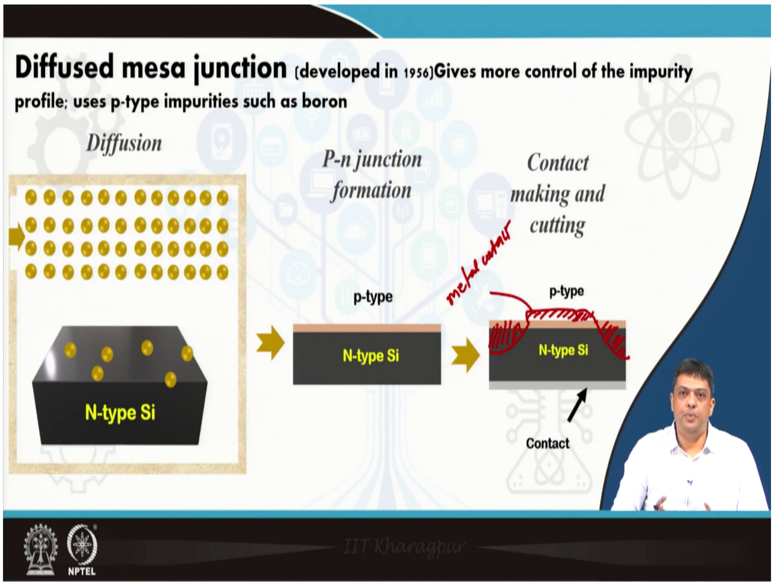

So, in the next technique, which is called the diffused mesa junction formation technique, which was developed around 1956 you could obtain higher control over the impurity profile and this uses the concept of diffusion, so what you do you?

You take an n-type silicon and on top of it you pass a gas of the impurity atoms which you want to diffuse in let us say boron and then when the diffusion happens, these impurity atoms diffuse into the n-type silicon. So in the previous case what you were doing, you were making a puddle you by heating and then you were forcing the atoms to diffuse because of the thermal agitation.

Here you are passing a gas and then you are allowing this atoms to diffuse in and that leads to the formation of a p-n junction and once you have formed this junction, you can protect certain region by forming metal contact or depositing an insulating layer and you can cut out these side regions using a HE and this gives you a p-n junction and if you also deposit contact on the other side, you will again get and so, if this is the metal contact you have two contacts and you can get a p-n junction diode.

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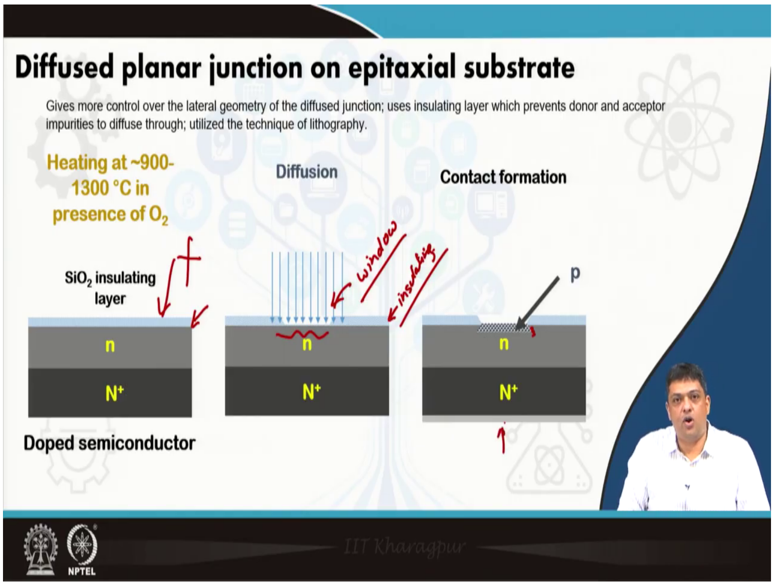

Then came the third technique which gave more control over the lateral geometry of the diffuse junction and this became very useful or prevalent after the discovery of lithography technique and the cost factor of using lithography technique came down significantly over the last 4 or 5 decades and that is where the diffuse planar junction on epitaxial substrate method became quite useful, so let us see what you have.

You take this n-type semiconductor heated to very high temperatures and because and in presence of oxygen when you heat at very high temperatures, you have silicon and you have oxygen that top layer you will end up getting the formation of an insulating layer and that is silicon dioxide, so oxygen flowing through the on top of the substrate leads to the formation of silicon dioxide, which is insulating.

Now, you have a substrate which is actually protected from any other damage be from other dopants, be from any other kind of impurities because, they cannot diffuse in because of this insulating layer which is also acting as a protective layer.

But, the idea is to make a p-n junction, so what should we do? Same concept we should actually have certain kind of diffusion process taking place or any kind of molten material which can be allowed to go inside the material with in this case the n-type semiconductor. So then you use the process of lithography it can be electron beam, it can be optical beam or ion beam lithography.

So, what you do you have a lithography system, you put your substrate use your plate which focuses the beam and then you use the photo resist which is coated on this material which gets exposed and then you can remove the area which is exposed while the other area remains on top of the substrate.

And once you dissolve this exposed photo resist you can then put a mask and then use the process of etching to remove this insulating layer in the region where you want the p-type impurity to actually diffuse in. So you open up a window, this is called window.

Now, through this diffusion can take place now, if I can have a similar flow of impurity atom, diffusion will take place only in this region, but not in the region which is protected by the insulating layer. So, I can control the region where I want to make the p-n junction and that is why this technique became very useful when we started making the integrated technologies.

So, now I want to make diffusion let us say I again use any kind of trivalent impurity which has to go in and once that is allowed to diffuse in you form a p-type region and once I form a p-type region I have a p-n junction formation.

Now, you see you have an n-type, you have a p-type, but you have an area which is remaining open to air to save any kind of impurity to actually diffuse in again in the p-type region you can make a contact and that will protect your p-type region and also will act as the contact for a device where you may have another contact made at the base of the substrate

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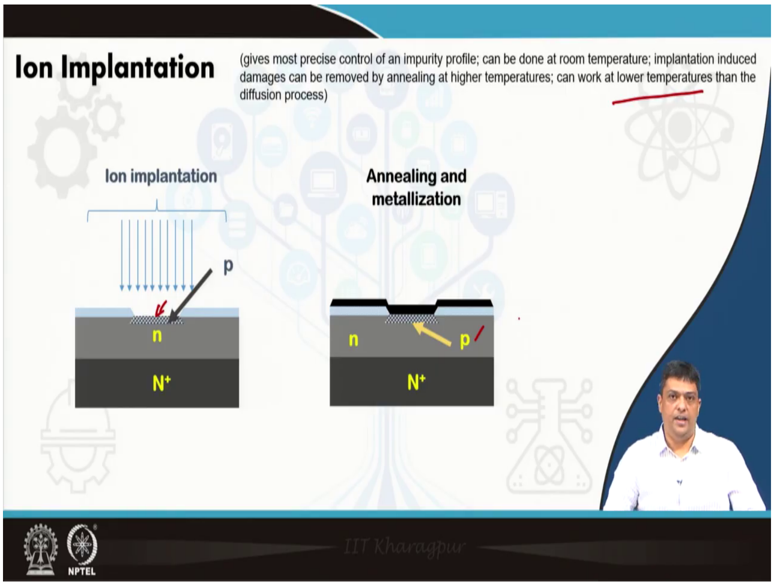

And finally the fourth technique, which is the most precise technique to obtain control over the impurity profile is ion implantation and this works on similar strategy which is used in the previous case.

Here only advantages is that it actually works at much lower temperatures, so if you were talking about diffusion processes, where you were operating at around 900 plus degree temperatures, this can be operating around 700 degrees or so and if you induce while the ions are actually being impinged into the area, while they are being impinged into the area, if you induce certain defects in the silicon lattice, if you can only anneal them at high temperatures, then these defects can actually be annealed out they can be removed.

So, this technique is called ion implantation. And again you can get the region of n and p and the formation of a junction and then on top of it, you can make the contacts and to remove the lattice defects which can happen you can use the process of annealing.

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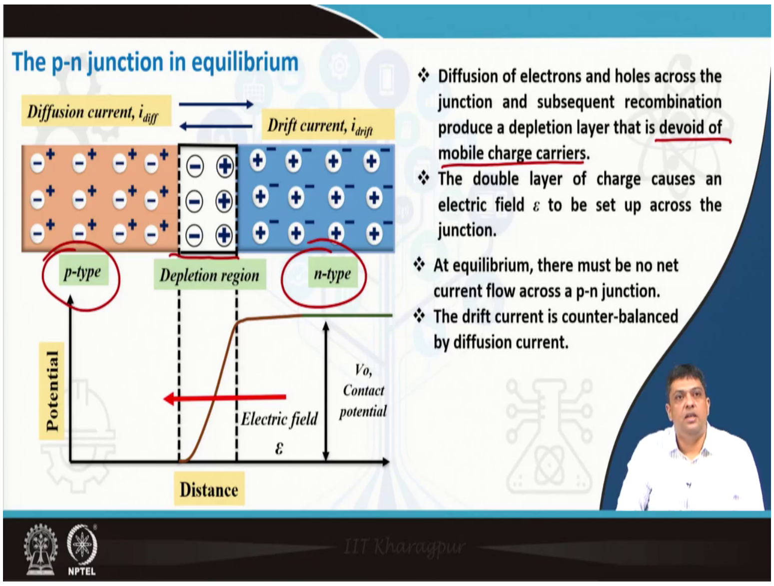

So, now once we have obtained p-n junction, I hope it is clear how do we actually form p-n junction what are the ways in which these p-n junction works. So, you have a let us say a p-type and n-type and a depletion layer because of the drift current and diffusion current you see that if you are having the flow you will get a region which is devoid of charges because there is a recombination of electron and holes, so you do not get any free charges in the depletion region.

So, you have a region which is devoid of mobile charge carriers, this double layer of charge causes an electric field which is set up in the p-n junction and that is acting across this junction and at equilibrium there must be no net current which flows at across this junction. So, at equilibrium, there is no flow across the junction, how is that prevented?

That is actually prevented by the drift current which actually counterbalances the diffusion current, so diffusion current when you have charges when they diffuse from one region to the other from a region of higher concentration to the region of lower concentration you are having diffusion current, but when you have regions where depletion layer no mobile charge carriers are available, then you have the drift current which comes into picture and counterbalances the diffusion correct.

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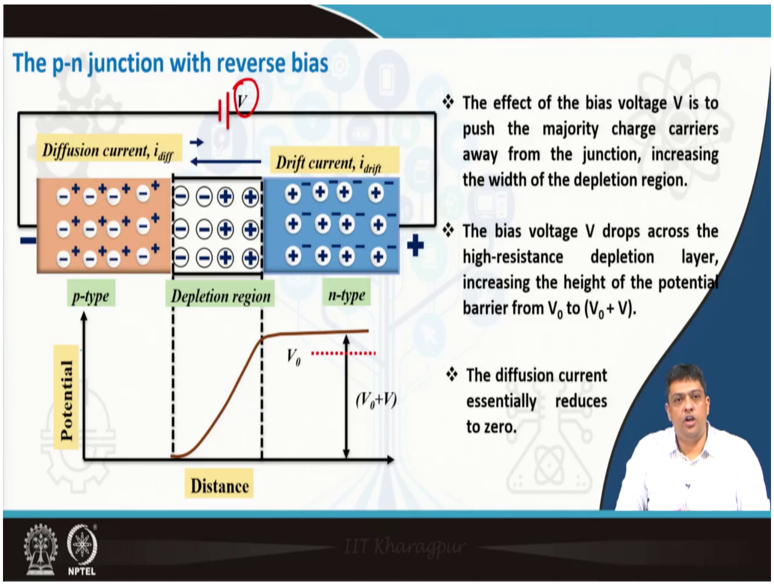

So, if you operate p-n junction under the reverse bias condition, it means that you are applying the polarities such that the majority charge carriers are pushed away from the junction and this increases the width of the junction. The bias voltage which you have used drops across the high resistance depletion layer and the height of the potential barrier now becomes V0 plus V and the diffusion current essentially reduces to 0.

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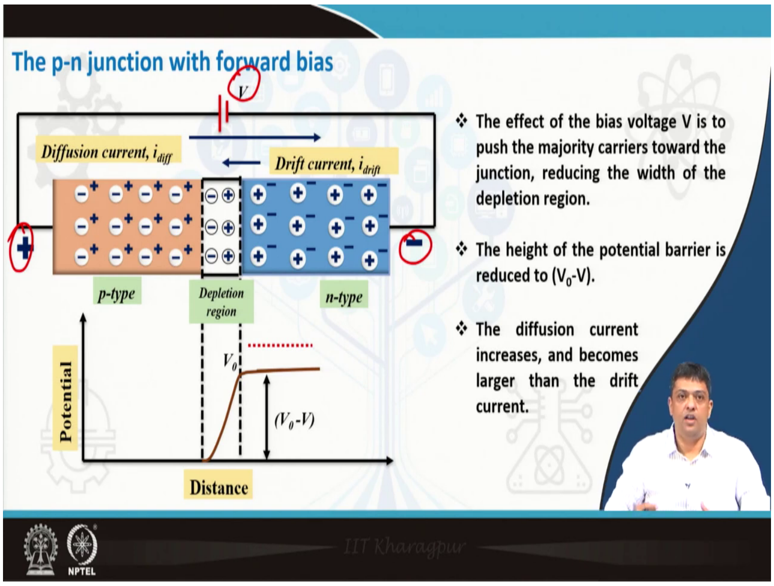

In comparison, if you are talking forward bias that means you apply polarities, which facilitates the motion of majority charge carriers then, you are actually forcing the majority carriers towards the junction and if more carriers are being forced towards the junction, then the width of the depletion layer actually reduces, the consequences the height of the potential barrier reduces to V0 minus V.

So, the height of the diffusion barrier also comes down and the diffusion current increases and becomes larger than the drift current, so you have diffusion current, which becomes larger than drift current.

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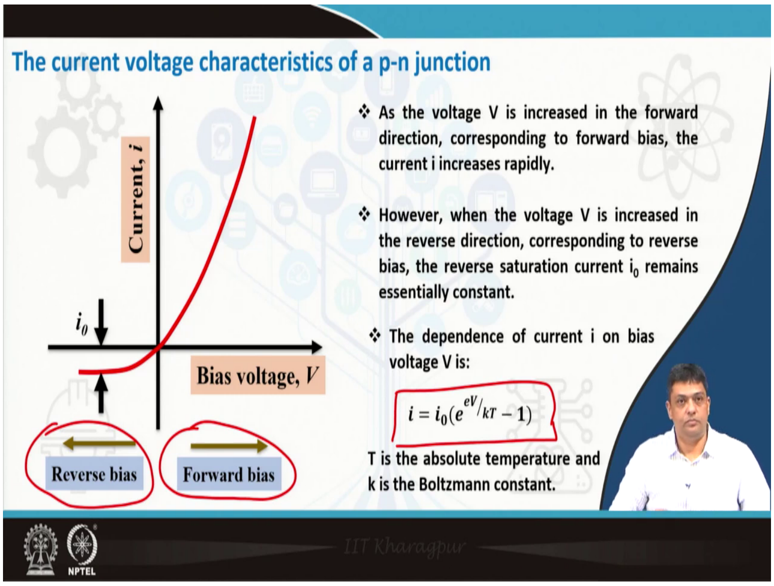

And if you plot the same concept in terms of IV curve, then this is what is seen in many books. In forward bias when you apply voltage, what happens the division current magnitude is more than that of the drift current that means, the current will increase by the application of voltage and the height of the barrier reduces to V0 and becomes V0 minus V so, if you apply more voltage more current would be flowing because the diffusion current would be larger.

This is what we had said in the earlier case and schematically this is your IV curve in forward bias and similarly, you can explain the reverse bias. So, the dependence of the current i on bias voltage V can be mathematically written as i is equal to i0 into e raise the power of eV by kT minus 1 where T is the absolute temperature and k is the Boltzmann constant.

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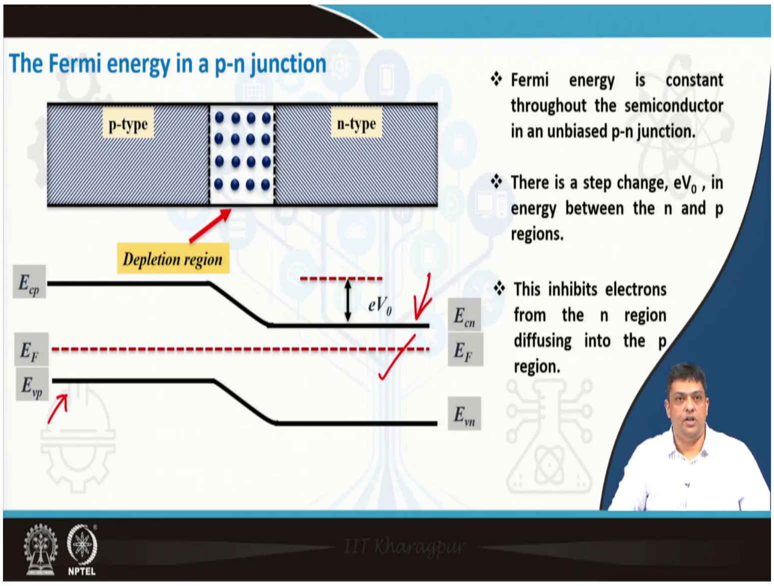

Again the Fermi level concept, so now, we were talking about Fermi level in individual p-type or n-type semiconductors now I have formed a junction, what happens to the Fermi level, this is one thing which you should understand.

So, Fermi level is constant throughout the semiconductor in an unbiased p-n junction, so you see the Fermi level remains constant when there is no bias in p-type semiconductor, you have your Fermi level which is nearer to the valence band whereas, in n-type semiconductor the Fermi level is nearer to the conduction band, this is what you have seen and you have the bank bending across the depletion layer.

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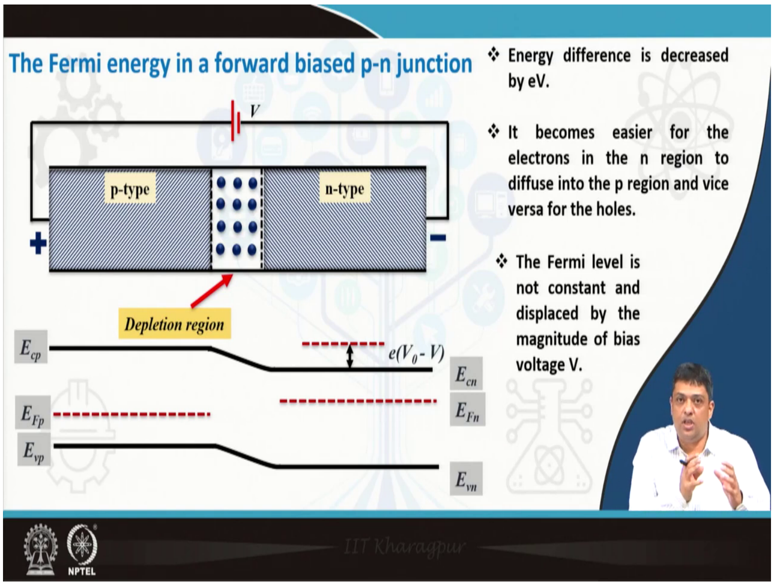

When you apply a forward bias what happens, the energy difference is decreased by e into V and it is becoming easier for the electrons in the n junction to diffuse into the p region and vice versa for the holes. Therefore, the Fermi level is not a constant anymore and displaced by the magnitude of the bias voltage V as we had explained earlier, the barrier is also getting reduced and therefore, you have flow of these majority carriers from one region to the other and if that is happening, the energy levels which are actually getting filled will be varying.

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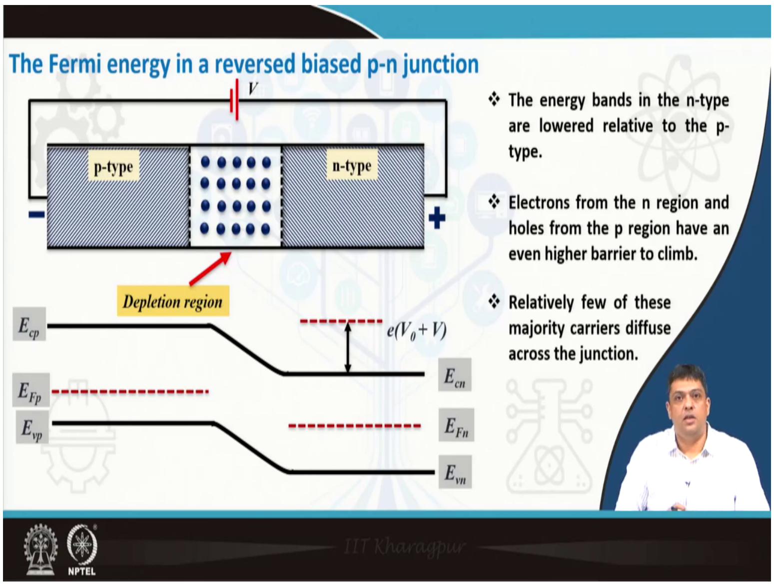

In the reverse bias just the opposite happens, what happens the electrons from the n-region and holes from the p region actually find a higher barrier to cross and so, there are a number of charge carriers which cross this barrier, that is the depletion layer region which I am talking about actually reduces and so, the Fermi level does not again remain constant and it actually varies and becomes and sees different values to what it had seen in an unbiased condition.

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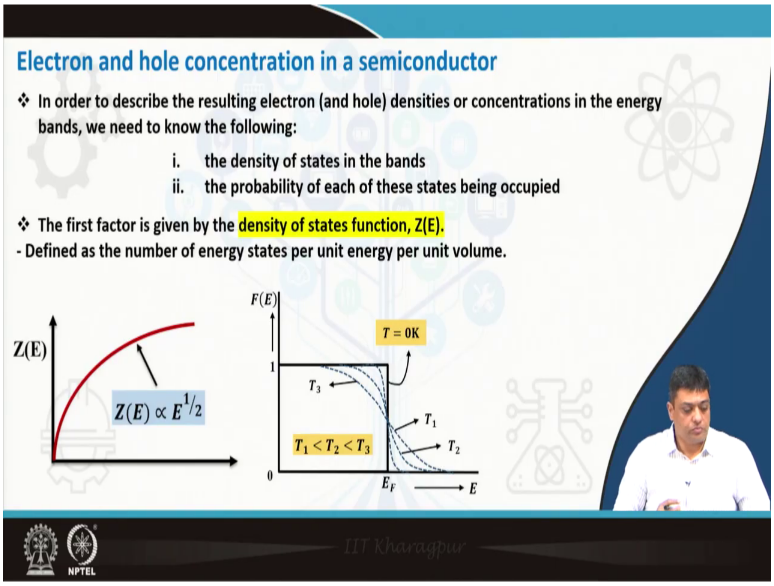

Now, you see you have an n-type p-type semiconductor and you have charge carriers. To understand what is the concentration of this charge carrier or majority charge carriers you should also understand the concepts of density of states in bands and the probability of each of these states being occupied. Let us start with the first factor that is the density of state. The density of state function Z of E is actually defined as the number of energy states per unit energy per unit volume.

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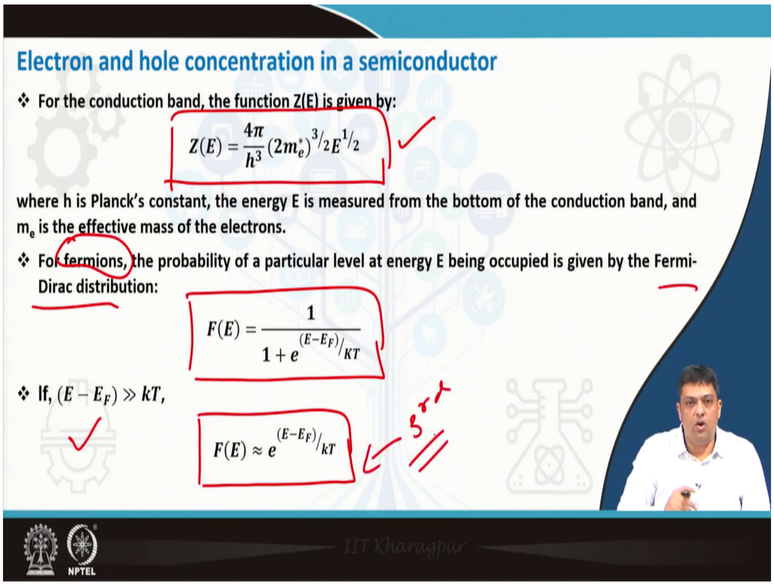

And for the conduction band, the value of Z E is actually given by the equation mentioned here, and we know that for fermions the probability of a particular level at energy E being occupied is given by the Fermi Dirac distribution.

So, we have fermions we know the functions Z E and how these will be filled and if the value of E minus EF is much larger than kT you get the Fermi Dirac function which is approximately equal to the third equation written on this slide.

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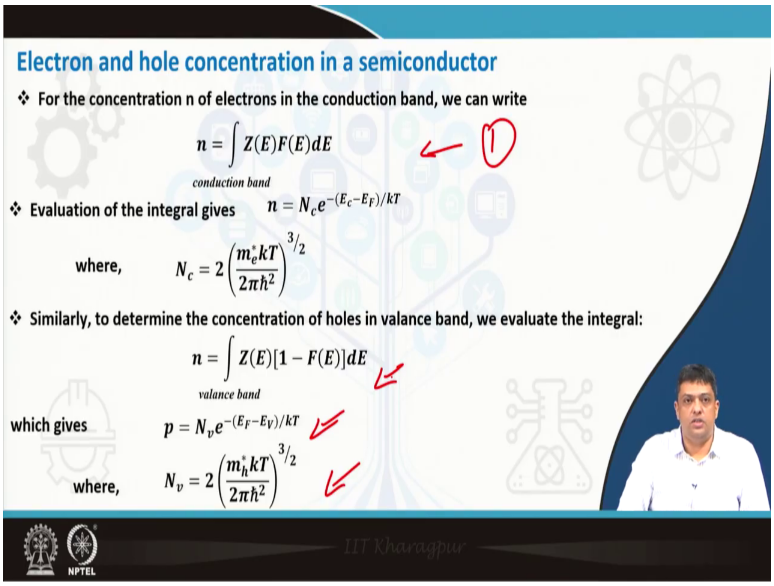

And using those equations, we can then again write that the concentration of electrons in conduction band can be written as ZE FE dE integration in the conduction band. Let us say question number one and the process of evaluating the integral has already been discussed in other courses on semiconductors and I will just use the relations mentioned in other courses. So, this is a typical way of calculating the electron and hole concentration in semiconductors and the product of the electron and hole concentrations is obtained by the quantity Nc Nv e raise to the power of minus Eg by kT.

Now, for a given temperature the product of n and p is fixed it, this concept is also applicable for extrinsic semiconductors and if we dope the intrinsic semiconductors with acceptor atoms to increase the concentration of holes, the concentration of electrons must therefore, decrease accordingly this is the inference which comes out from the first two points. And in case of intrinsic semiconductor the product of n into p is equal to ni squared.

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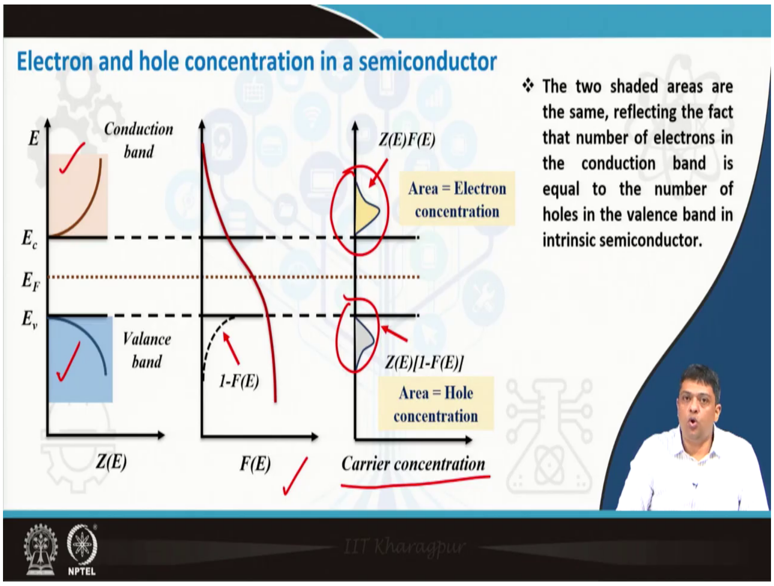

So, you can plot the various functions either you can plot ZE FE as a function of E or carrier concentrations, you can see that the two shaded regions are same reflecting the fact which I said in the previous slide that the number of electrons in the conduction band is equal to the number of holes in the valence band in intrinsic semiconductors and then you can plot the Fermi Dirac functions also or Fermi energies can be then drawn in case of intrinsic or extrinsic semiconductors. And then you can draw the variation of carrier concentrations. So, you can have the variation carrier concentration in n-type region or p-type region.

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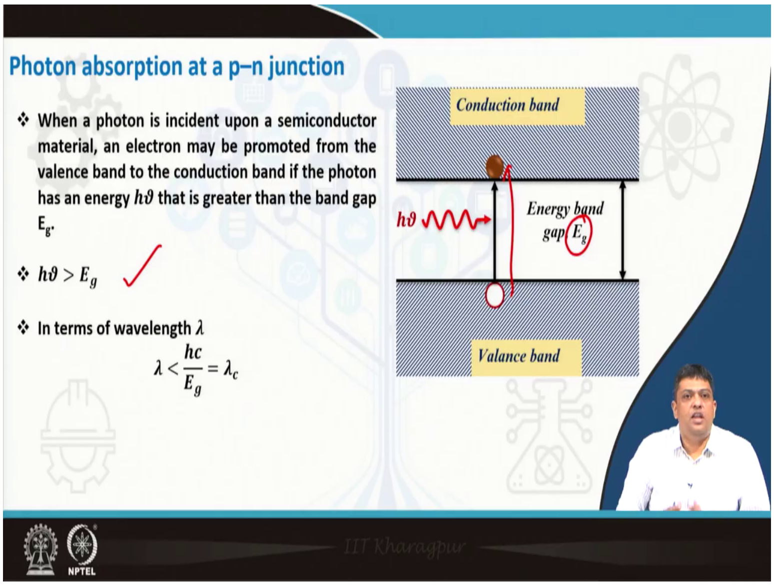

Now, let us see what happens you have a valence band you have a conduction band and you have an energy band gap. So, now let us say a photon is incident on this system if the energy is such that it is able to induce a jump from the valence band to the conduction band, you will have a change in the conductivity, this is what we are just trying to infer from the condition just mentioned.

If the energy is less than Eg, what will happen, what do you think, will there be any transformation from valence band to conduction band? I do not think so and I think you will also have the same opinion, if the energy is more than the energy of band gap that is h nu greater than Eg you will see some absorption of photons and leading to transformation from valence band to conduction band for electron and in terms of if we write the same condition in terms of wavelength, we have if lambda is less than hc by Eg then we have the transformation taking place.

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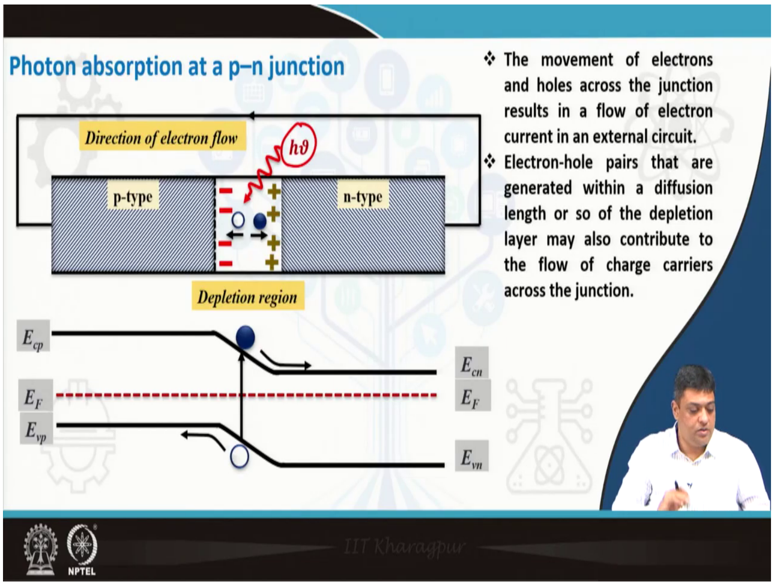

If you now try to understand the concept of the flow of electrons and holes, when there is an absorption of a photon, do you think that we are slowly moving towards the formation of a solar cell? I think you will be understanding that yes, we are trying to explain how does a solar cell actually works, it is only that we need to have the energy of these photons, which are large enough to break these annihilated charges.

So the immobile charges which were being formed because of the in E combination of holes and electrons, if you are able to excite them in such a manner, then they again get separated then, because of the electric field which is present across the junction, that two charges will flow and that will lead to the formation of a solar induced cell and that you will call as solar cells, this is what we are indicating towards.

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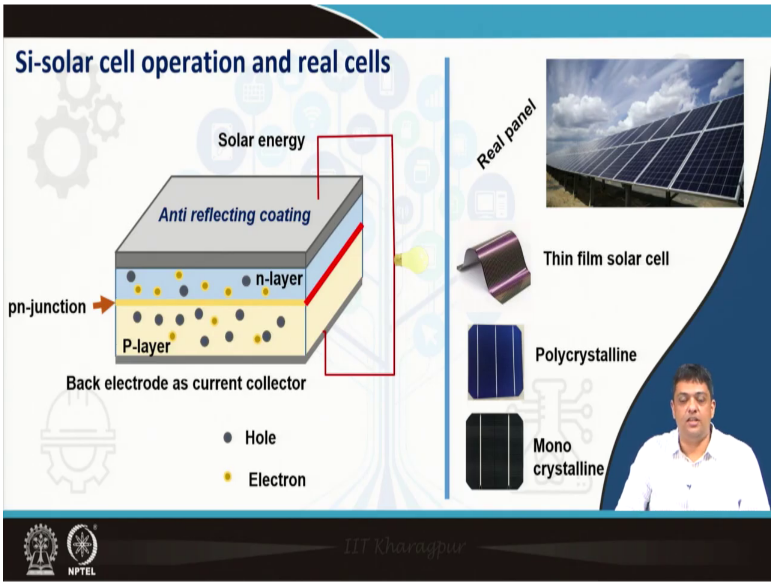

And that is what is actually done in a solar cell. What do you do? You make a n type layer, a p-type layer and a junction, when you have an incident photon which is falling on the depletion layer in which is formed across this p-n junction, it breaks the immobile charges and then because of the formation of mobile electron and hole, if you connect them across the external load, the electrons will flow through the external load and then recombine with the holes in the P region, so that the condition of charged reality is once again obtained and insured for an overall system and that will lead to the formation of a solar cell.

And these are the real panels which are now available in the market you can have thin film solar cells, you can have poly crystalline silicon solar cells or you can have mono crystalline solar cells.

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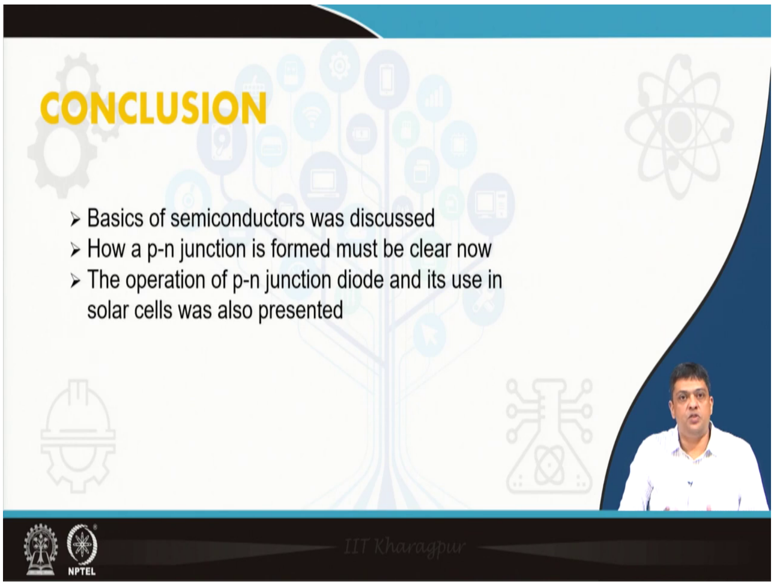

So, hopefully in today's lecture using the basics of semiconductors, I have explained to you the formation of a p-n junction, the formation of a depletion layer in this p-n junction diode and then how the concept of illuminating this depletion layer in a p-n junction diode can be used to fabricate a silicon based solar cell.

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These are the references which I have used in today's lecture and I thank you for attending the today's class and from next lecture onwards, we will start understanding more details about the characterization of solar cells and the mathematical formulations which are used to give values to the various parameters related to a solar cell. Thank you very much.