Solar Energy Engineering and Technology
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Lecture 10
Semiconductor Physics

Dear students, today we learn Semiconductor Physics. So, before we start, let us summarize, what we have discussed in the last class.

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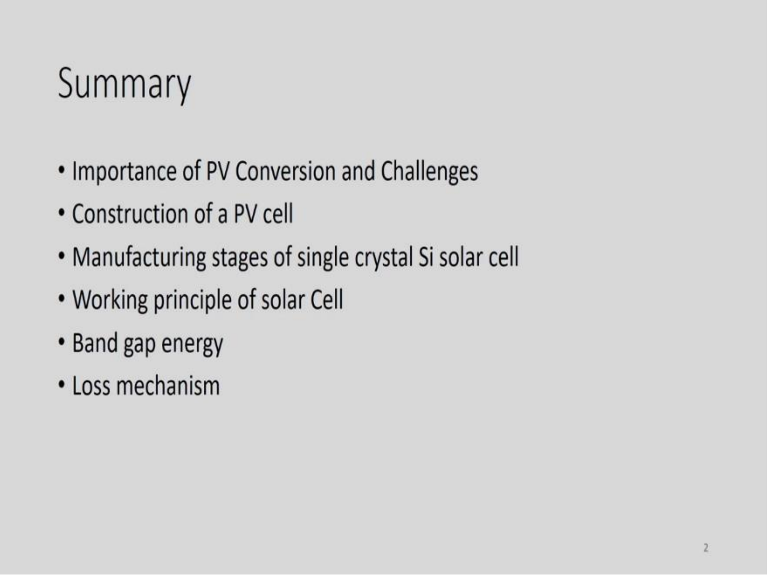

So, we have studied importance of PV conversion and challenges. Then construction of PV cells, what are different layers, how different layers are formed, as a whole what is the construction of a solar PV cell. Then manufacturing stages of a single crystal silicone solar cells, we have studied. And what is the working principle of a solar cell, that also elaborately discussed in the class. And band gap energy was discussed. And finally, loss mechanism were discussed in the last class.

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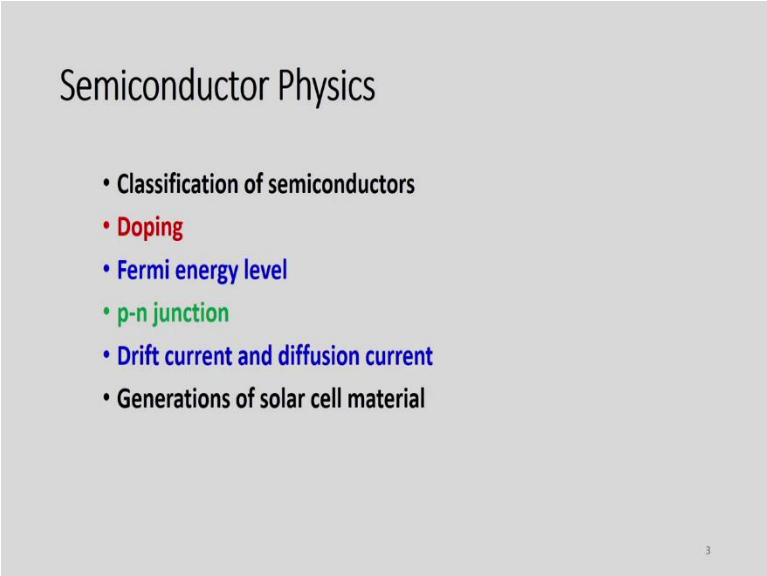

Now, come to this class. So, we will be covering classification of semiconductors, doping, fermi energy level, p-n junction, drift current and diffusion current and generation of solar cell material.

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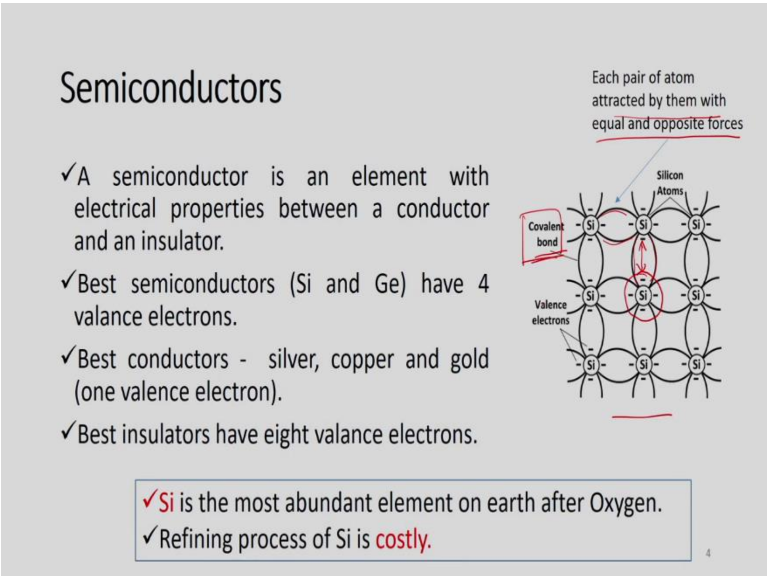

So, what is semiconductor? A semiconductor is an element with electrical properties between conductor and an insulator. So, best semiconductors are silicon and germanium, having four valence electrons. And the best conductors are silver, copper and golds. In the conductors, only one valence electron will be present. For insulators, there will be 8 valence electrons. Example of insulators are like glasses, are the prime example. And if we talk about silicon material, as we understand that 90 % of the solar cells are made of silicon-based wafers.

So, let us concentrate more on these silicon solar cells. The silicon, silicon Si, is the most abundant material or element on earth, after oxygen. But if we have to use it for solar cell applications, so we need to do refining process which was discussed in the last class, which is very very costly. As we can realize, we need huge of equipment and that has to be maintained at very high temperatures. So, it is a very costly affair while making this metallurgical grade to semiconductor grade solar cells.

Now, if we look at this picture, what I have shown here, it is a crystal. So, it is a silicon crystal. So, there are many cells are composed of a crystal or solids. So, we have defined what is crystal in the last class. So, this, for example, if we consider this is a silicon atom and this silicon atom has 4 valence electron. And in this atom what happens, they share these electrons with the neighbouring atoms. So, 4 atoms, they are sharing their 4 valence electrons. And they make pairs. And this each pair, each pair of atom attracted by them with equal and opposite forces. So, this will attract this way and this electron attract this way. So, as a result, they make some kind of bond. That bond is called covalent bond.

So, this covalent bond is very very important. This gives the solidity to this crystal. It gives the binding, how tightly this crystal is bind? So, when we need to lift this electron, then we have to have some kind of energy supplied externally. So, we will discuss this matter in the coming slides. So, what I tried to present here, these atoms, they have 4 electrons and they share with the neighbouring atoms and they make pairs. And these pairs of atoms attracted by them with equal and opposite forces and they make a chemical bond called covalent bond. And this covalent bond give solidity to the crystal.

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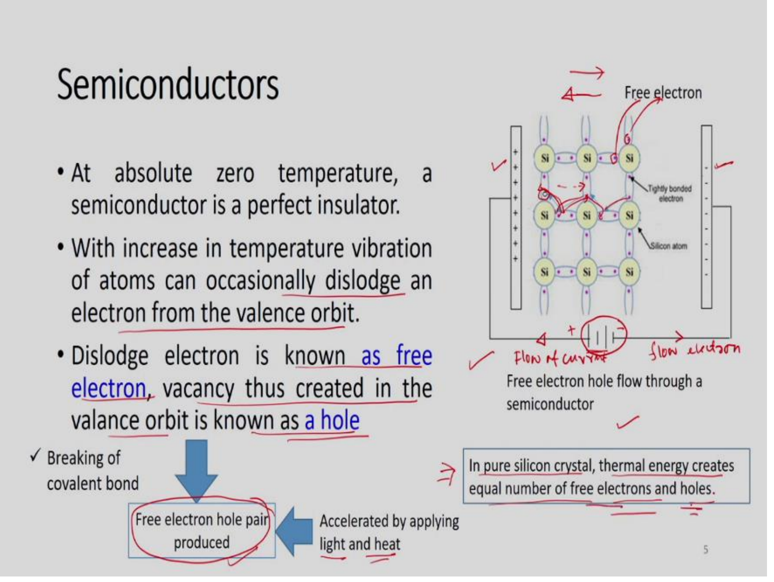

So, at absolute zero temperature, a semiconductor is a perfect insulator. No current will flow, if we maintain at the temperature of 0 degree kelvin or 0 K. With increase in temperature, vibration of atoms can occasionally dislodge an electron from the valence orbit. So, this dislodge electron is known as free electrons. So, this is important. And when this happens, this vacancy which is created in the valence orbit is known as a hole. Thus, it breaks the covalent bond. And once this breaks the covalent bond, this free electron hole pair produced. And we can increase this free electron hole pair generation by supplying light and heat. So, in a pure silicon crystals this thermal energy creates equal number of free electrons and holes. That you should keep in mind.

Now, let us see this figure which shows the free electrons and holes flow through a semiconductor. So, what happens, this is a metal strip and this is a metal strip, this is negatively charged and this one is positively charged. And these are free electrons, these are free electrons. So, this is positive, this is negative. And flow of electron will be, this is flow of electron and flow of current will be here, flow of current, flow of current. So, if we provide some kind of potential to this intrinsic semiconductor, so all the atoms in the crystals are silicon atoms.

So, here what happens, electron, this free electron will move from this negative side to the positive side. So, this will travel something like, if we consider this free electron, this will move here and then this will move here and then this will move here, something like that. But this hole, this is an hole, which is near to these positively charged plates, what they will do?

This will try to move in the other way, because electron will move this way and hole will move this way.

So, what we can understand, this electron will move from negatively charged plate to the positively charged plate and it flows through this circuit and it completes it. But the holes will move from here to here, this side. So, electron movement will be from negative side to the positive side and hole movement will be from positive side to the negative side. So, this is what we try to understand.

So, in case of silicon crystals, so all the atoms are silicon, no impurities are added here. So, when we connect it, so electron, this free electron will move from this negatively charged plates to the positively charged plates and they completes the circuits and they maintain this scenario. But we must know in a pure silicon crystal, the thermal energy creates equal numbers of holes and electrons. That we should keep in mind.

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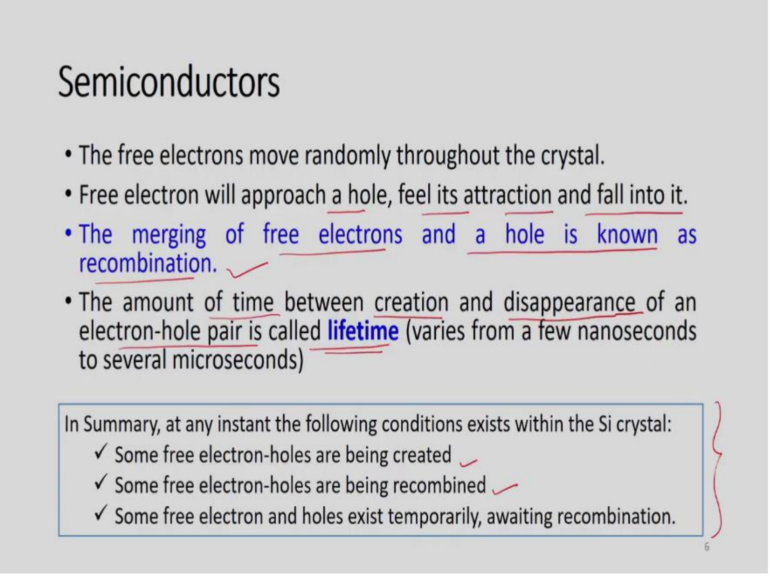

So, the free electrons move randomly throughout the crystal and then free electrons will approach a hole, feel its attraction and fall into it. So, merging of free electrons and the hole is known as recombination. Already in the last class, we have discussed about the recombination, but still we need to understand these things because this is one of the important aspect as far as PV conversion is concerned. So, this merging of electrons and the holes is known as recombination.

The amount of time between the creation and disappearance of an electron hole pair is called lifetime. And this lifetime varies from few nanoseconds to several microseconds. So, in summary, what happens, when we supply potential to this crystal, then what happens in summary, some free electron holes are being created, some free electron holes are being recombined and some free electron and holes exist temporarily and waiting for recombination. So, in summary, this phenomenon happens when we provide potential to this crystal.

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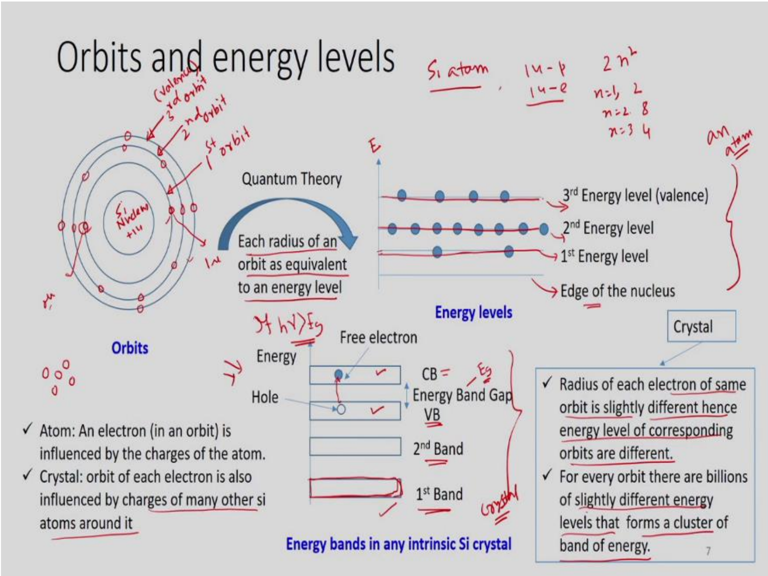

Now, let us learn about orbits and energy level. So, what I have shown here, it is an orbit. So, normally we take help of quantum theory to understand properly about the semiconductor characteristics. So, in quantum theory, what approximation is considered as far as orbit and energy level is concerned, that each orbit or say each radius of an orbit is equivalent to an energy level. So, as you understand, in case of silicon atom, what happens, we have 14 protons and then 14 electrons. So, as we know this principle $2n^2$. So, what happens if for n=1, so orbit 1, so it will be 2. If n = 2, then it will be to 4 × 2, 8. And then n = 3, so here since it is 14 electrons, so in a valence orbit, we will have 4 electrons.

So, if we consider this is silicon nucleus, silicon nucleus and we have 14 protons. And in this first orbit, we will have 2 electrons and in second orbit, we will have 8 electrons; 1, 2, 3, 4, then we have 5, 6, 7, 8 electrons. And in the valence orbit, we will have 4 electrons, 1, 2, 3, 4. So, we can write, this is the first orbit, first orbit and this is second orbit and this is third orbit, third orbit or valance orbit, or valance orbit, or valance orbit.

Now, what happens, we will study very critical phenomenon here. So, this is for an atom or that has to be intrinsic. And this is for crystal. So, as we said, we take the approximation, so we use quantum theory and the approximation is something like, each radius of an orbit is equivalent to an energy level. So, this is energy E here in the vertical direction and these are the electrons, at different energy level. So, this is the, this is actually edge of the nucleus and this is first energy level, second energy level, then we have third energy level.

So, normally what happens? In the orbit, an electron is influenced by charges of the atom. So, any orbit you consider, this so, then electron is influenced by charges of the atoms. So, if we take an isolated atom, its energy level will be something like that. So, it is defined. So, there is no variation of the radius of the electrons.

But when we consider crystals, in the crystal, as you can understand now, there will be many atoms, there will be many atoms. So, and then they have occupied in a certain position. So, we cannot compare the charges of the each electron or each atom is similar. What I mean to say, suppose, for example, if we consider this electron, so if we consider single atom, its fine, its radius will be same. But if there are multiple atoms, then radius of those maybe, if you consider, this one, this one, this is originated from one atom, one atom and this is originated from other atom. So, its radius may vary.

So, what happens in crystal, orbit of each electron is also influenced by charges of many other silicon atoms around it. So, this radius of each electron of the same orbit is slightly different, hence energy level of the corresponding orbit, orbits are different. So, this energy level will be different. So, we cannot write a single line here, what I have drawn for a single atoms or a single silicon atoms. So, this is very, very important. So, one more time I am reading it that the radius of each electron of same orbit is slightly different, hence energy level of corresponding orbit, orbits are different.

So, for every orbit, there are millions of slightly different energy levels. You can see, there are millions of slightly different energy levels that forms a cluster of the band of energy. So, that is why, you can see this kind of blocks, not a single line for crystals. This is very, very important. So, these kind of blocks normally we get. So, that indicates there are billions of different energy levels and that is known as band or say, that is a cluster or say, band of energy. So, that is why, this is the first band, this is the second band, this is valance band, this is conduction band.

Now, if we have to lift one electron from this valence band to the conduction band, then what we need to do? If we represent this band gap is E_g and certain amount of energy if we supply, then this energy, if this energy, see may be *hυ* energy is more than this E_g, then what will happen, this electron will move from valence band to the conduction band. So, this is how it works.

But in case of intrinsic semiconductor, where no dopants are presence, all our pure crystals of silicon crystals, so number of holes and number of electrons will be same. So, if this is connected to a potential, then what will happen? So, the electrons will occupy in the conduction band and holes will occupy in the valence band. Then under that condition, no current flow will be there. So, that is why, we need to do something so that we can make use of this p-type and n-type semiconductors for practical use. So, let us learn how this p-type and n-types are created and what is intrinsic semiconductor and what is extrinsic semiconductor.

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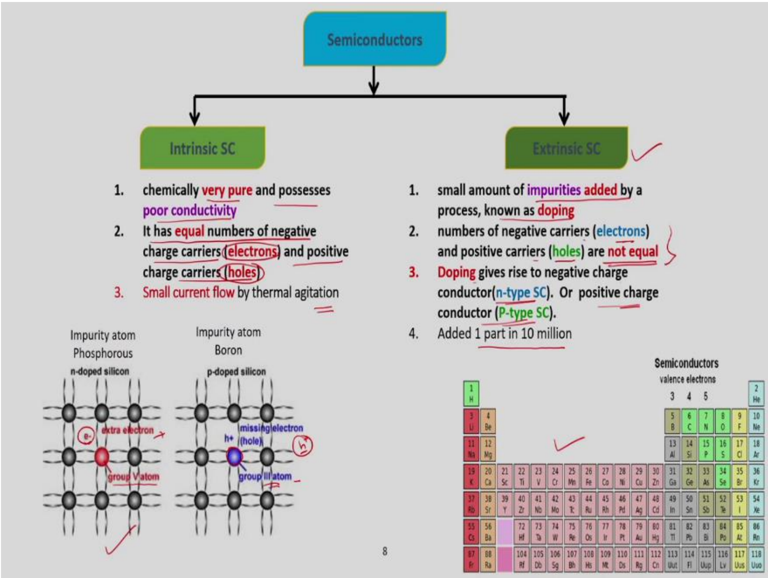

So, here, we will have semiconductors, there are two classes one is intrinsic semiconductor, I have been using this terminology and then second one is extrinsic semiconductor. In case of intrinsic semiconductor, which is not doped, pure crystals are there, only if we talk about silicon crystal, only silicones are present, silicon atoms are present to constitute that crystal. So, these are chemically very pure and possesses very poor conductivity. So, this is one of the disadvantage. And it has equal number of negative charge carriers and positive charge carriers.

So, when we talk about negative charge carriers, these are electrons and positive charge carriers are called holes. So, small current flow by thermal agitations. So, this is not a practical applications, so when we talk about intrinsic semiconductor.

So, in case of extrinsic semiconductor, the small amount of impurities are added. So, some kind of impurity atoms are added. So, there are different impurity atoms. So, maybe we can use of this our chart. So, from that we can identify which element we need to use for doping. So, small amount of impurities are added by a process known as doping. And number of negatives carriers, that is electrons and the positive carriers, holes are not equal. So, this is very, very important.

And doping gives rise to negative charge conductor, that is n-type semiconductor and positive charge conductor is called p-type semiconductor. So, how much normally added, how much impurities are added in a pure crystal, is about 1 part in 10 millions, which are very, very small. Again, there are certain issues when to add and how much to be added. So, it is related to resistance of that particular semiconductor.

So, what is shown here, that is, when pentavalent impurities are added, so extra electron will be generated here. And when group 3 atoms like borons is added, so holes hole will be there. So, these electrons are actually donors and these holes are acceptors. So, when these group 5 atoms like phosphorus is added, so that material is called n-type semiconductor. If trivalent atom called boron is added that doped semiconductor is known as p-type semiconductor. So, this is important classification. So, we will use it for the next analysis.

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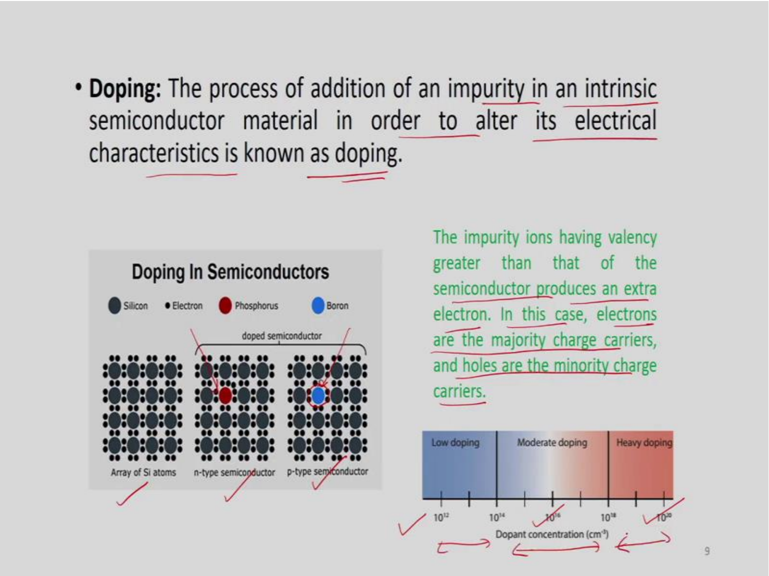

So, doping, what is doping? The process of addition of impurity in a, in an intrinsic semiconductor material in order to alter its electrical characteristics is known as the doping. So, again we have shown here, it is a silicon, array of silicon atoms and n-type semiconductor and p-type semiconductor, where in the p-type semiconductor, this boron is used as a impure atom and here phosphorus is added as impure atom.

So, this impurity ion having valency greater than that of the semiconductor produces an extra electron. In this case, the electron, electrons are the majority charge carrier and holes are minority charge carrier. So, as I said, there are different levels of doping. There may be certain cases where low doping is important and some kind of moderate doping and some kind of heavy doping. So, you can see the ranges of dopant concentration here. This is a dopant concentration for three cases. So, for lightly doped semiconductors have high resistance, whereas a heavily doped semiconductor has low resistance, that you should keep in mind.

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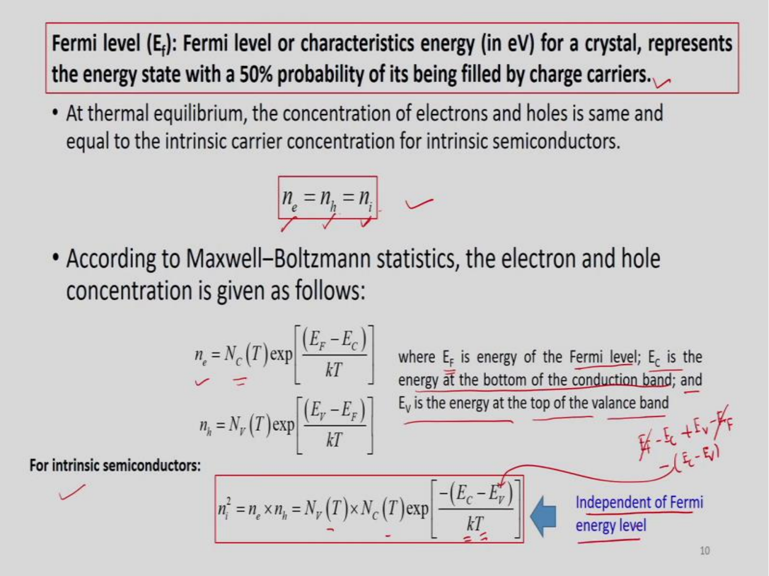

Now, come to the Fermi level. What is Fermi level? Fermi level or sometimes it is known as characteristics energy and which is represented in eV, for a crystal represents the energy states with a 50 % probability of its being filled by charge carriers. So, we will understand when we draw this band diagram. Now, at thermal equilibrium, what happens is concentration of electrons and holes is same in case of intrinsic semiconductor. So, if this is the case then what we can write. If we represent the concentration of electrons is n_e and concentration of hole is n_h and this is something like, for intrinsic carrier concentration n_i. So, this is the condition.

And according to Maxwell-Boltzmann statistics, the electron and hole concentration is given by $n_e = N_C(T)\exp\left[\frac{E_F - E_C}{kT}\right]$. And then $n_h = N_V(T)\exp\left[\frac{E_V - E_F}{kT}\right]$. So, this E_F is the energy of the Fermi level and E_C is the energy at the bottom of the conduction band. So, we will see when you see that slide of band diagram and E_V is the energy at the top of the valence band.

So, for intrinsic semiconductor, so we can write, since $n_e = n_h = n_i$, so $n_i^2 = n_e \times n_h$. So, this will be something like this. Since, this is exponential, so this will be plus. So, this is something like (E_F - E_C + E_V - E_F). So, this will be something like, this will goes off. Then if we take this minus this side, then (E_C – E_V) will be there here. And here k is the Boltzmann constant and T is the temperature in Kelvin. So, these are the coefficients. This expression is independent of Fermi energy level. If I am interested to express in terms of Fermi energy level, of course, we can do it. So, how we can do it, let us see in the next slide.

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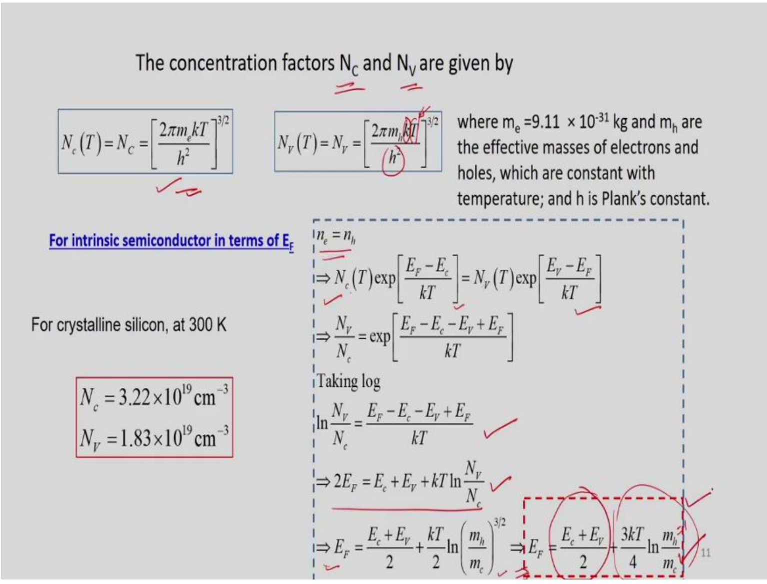

So, we know this concentration factor N_C and N_V are given by something like this. So, this m_e and m_h are the effective mass of electrons and hole respectively. And these are the constant, k is the constant. So, h is also constant, then we have T is the temperature. So, it will vary with the temperature. So, now, our primary intention is to develop the expression in terms of Fermi energy level.

So, already we know for intrinsic semiconductor, $n_e = n_h$. So, we can use those expressions what we have explained in the last slides. So, expression for ne is something like this and n_h is something like this. And if we take N_V/N_C, so this, this divided by this part, so this will come other side. So, this will be (E_V - E_C - E_V + E_F)/kT. So, if we take log, then what we will have, this will be something like this. And then, if we adjust those values and finally what we will have, this expression. And if we substitute this expression here what we have, then we can relate this expression in terms of m_h and m_c. So, finally, if we simplify, then our expression will be something like this.

So, what we can understood from here, since for intrinsic semiconductor, m_h and m_c are same. So, what happens, this part will be 1. So, ln (1) = 0. So, this part will be 0. So, this E_F, this Fermi energy level is, at the centre of the conduction band and valence band energy. So, that is what it is derived. So, it is very, very effective to understand why for intrinsic semiconductor, E_F is at the centre of the conduction and valence band.

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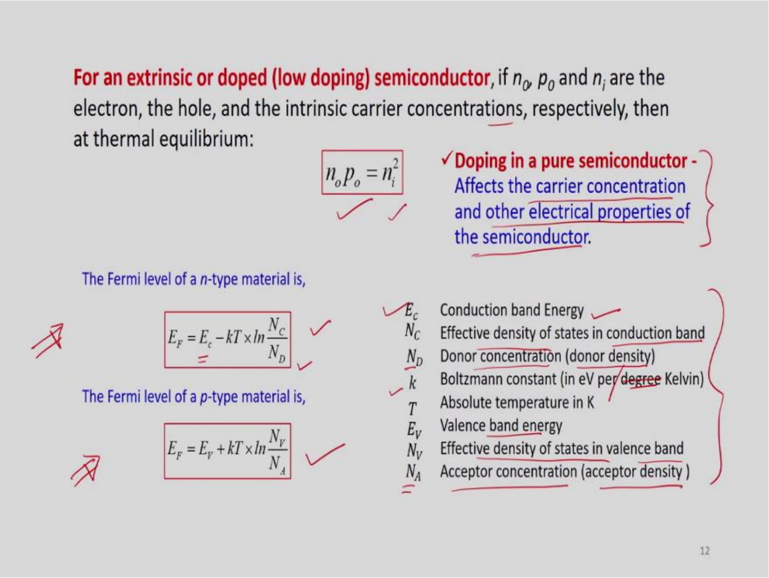

So, now what happens in case of extrinsic or doped semiconductor? So, if n_o and p_o and n_i are the electron holes and the intrinsic carrier of concentration, then the thermal equilibrium will have $n_o \times p_o = n_i^2$. This is the things normally happens. As we know, this doping in a pure semiconductor affects the carrier concentration and other electrical properties of the semiconductor. So, that is how, this expression is different. And straightaway, what we can use, the expression for calculation of Fermi energy level for n-type semiconductor material. So, this is [E_C - kT×ln (N_C/N_D)].

This is E_C is the conduction energy and N_C is the effective density of states in the conduction band and N_D is the donor concentration, it is donor density and k is Boltzmann's constant. Already we have defined and its unit is eV/K not degree. So, centigrade means it is degree, and T is in absolute temperature which should be in Kelvin and E_V is the valence band energy and N_V is the effective density of states in the valence band and N_A is the acceptor concentration or acceptor density. These are the terminology used and we can use these two expressions for calculation of Fermi energy level for n-type and p-type material.

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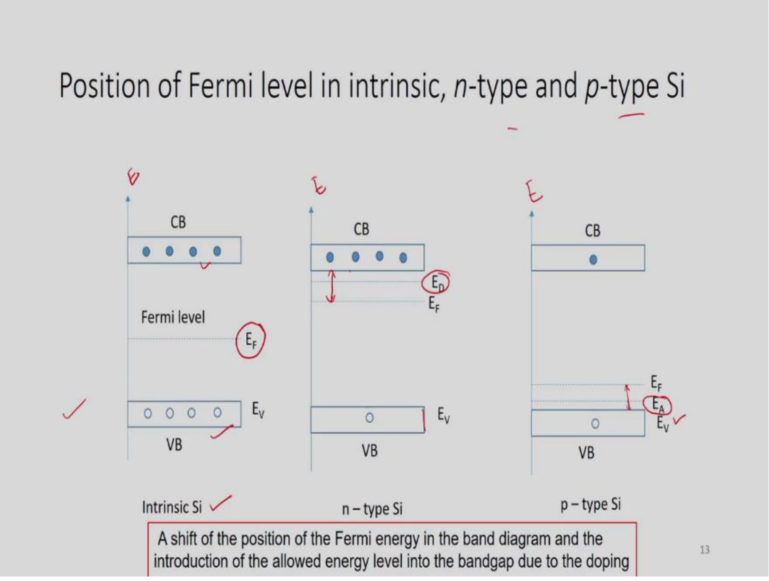

So, as we have explained before, to know this position of Fermi energy level in intrinsic n-type and p-type semiconductor, it looks something like this. So, it shows the shift of position of Fermi level in the band diagram. So, here what happens, this is energy, this is energy, this is energy. So, in case of intrinsic semiconductor, what happens, this Fermi energy level is at the centre of the valence band and conduction band. So, number of holes and electrons are same.

So, here in case of n-type semiconductor, this Fermi energy level will move towards conduction band. Because number of electrons will be more here, majority charge carriers are electrons. In case of p-type semiconductor, since majority charge carriers are holes, this E_F will shift to towards valence band. So, these are the different configurations. Also, we have learned why this is thick and what happens. So, this is the energy level for donor and this is the energy level for acceptor. So, it should not come to, these are valence band, but there should be very close It is close to valence band and this is close to conduction band. So, if it comes to here, then it becomes a conductor. It will be no longer semiconductor. If it will come here, then it will becomes like insulator.

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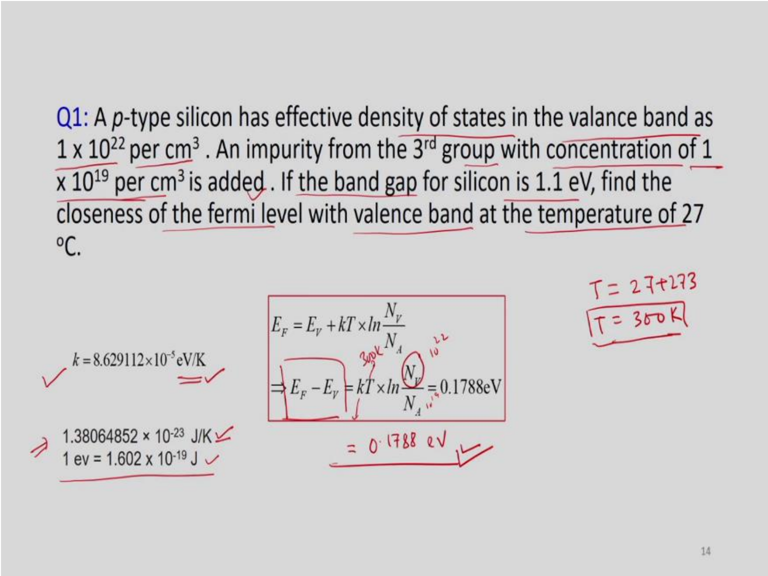

So, let us solve one problem. So, this problem statement goes something like this. A p-type silicon has effective density of states in the valence band as 1×10^{22} cm^{-3}. An impurity from third group with concentration of 1×10^{19} cm^{-3} is added. So, this much of impurities are added. And band gap of silicon is given you as 1.1 eV. Find the closeness of the Fermi level with valence band at the temperature of 27 °C.

So, temperature, as I say this temperature has to be in Kelvin, so it will be (27+273), it will be 300 K. So, temperature is 300 K. And also we know this value of k is 8.629112×10^{-5} eV/K. So, also we must know the value of k in J/K. And also, we know 1 eV = 1.602×10^{-19} J. So, sometimes if we know this value, then and this value, we can convert it as per our requirement.

So, if we can use this here straightaway, then we can do the calculation, because this value is known to us. So, N_V is 10^{22} and this is 10^{19}. So, k value is given and T is 300 K. So, if you substitute here and do this calculation and it is found to be 0.1788 eV. So, this difference is that much of eV. So, we can generate numerous problem for understanding this phenomena.

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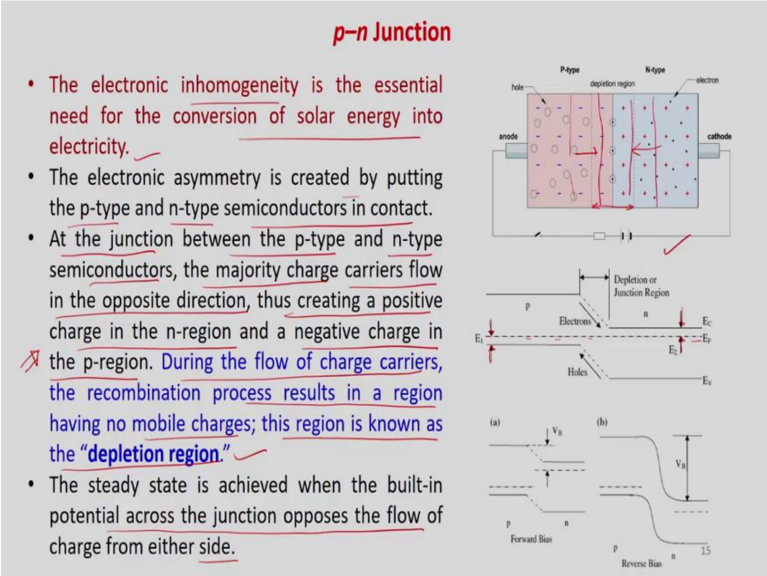

Now, let us come to the p-n junction. So, so far what we have learned is intrinsic semiconductor and then we have extrinsic semiconductor and then dopant, what are the dopant used, and then that becomes your n-type semiconductor and p-type semiconductor. Now, what we are doing, these two n-type and p-type semiconductors are joining together, that becomes a junction. So, why happens when we are joining these n-type and p-type semiconductors. So, you can see these simulations, what is going on here.

So, as soon as it comes contact with p-type and n-type, what happened, the electron in the n side will move to the p side and holes from the p side will move to the n side. And they make a depletion layer. In the depletion layer, again, there is a transfer of electron from n side to the p side. So, due to this flow of electron, there is a current flow, that flow of current is known as diffusion current. We will learn this in the next slides. And we have to define drift current, when it is connected to forward bias system and also breakdown voltage when it is connected to reverse bias system.

So, now, in summary, let us discuss these points like the electronic in homogeneocity or homogeneity is the essential need for conversion of solar energy into electricity. The electronic asymmetry is created by putting the p-type and n-type semiconductor in contact. At the junction between the p-type and n-type semiconductors, the majority charge carriers flow in the opposite direction. Thus, creating a positive charge in the n-region and negative charge in the p-region. This part has already been discussed when we were discussing the working principle of solar cells. During the flow of charge carriers, the recombination process results in the region having no mobile charges. This region is known as depletion region. So, this is also known as depletion region. So, this part is depletion region.

The steady state is achieved when the built-in potential across the junction opposes the flow of charge from either sides. So, what happens in case of reverse bias, as you can see, so this depletion region will increase, but in case of forward bias, this depletion region will contract. So, that is what, it is shown here. So, as we know, when we connect this, this has to be maintained in the centre and this has to be almost constant for both the sides.

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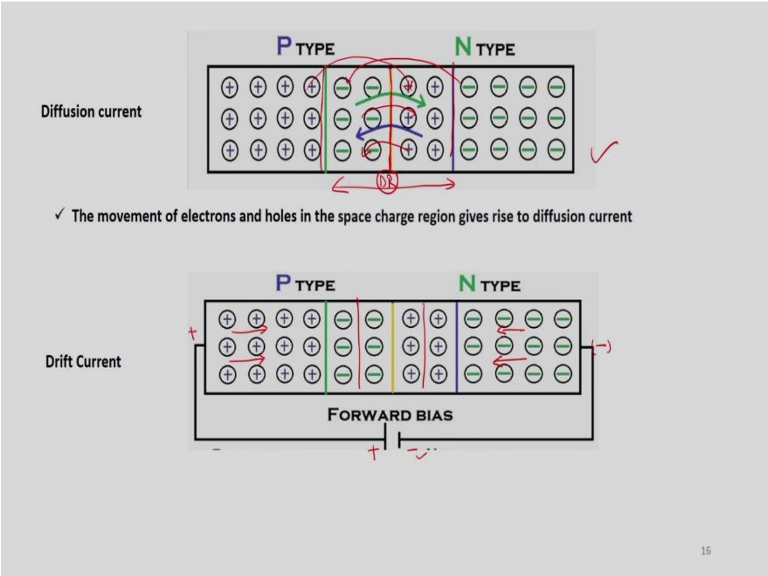

So, see in case of, say when we are not connecting this p-type and n-type with external sources, then what happens, when we join this n-type and p-type semiconductor, then this becomes a junction. So, as soon as we join these two, then negatively charged electron will move to this region and positively charged electron will move to this region. So, they make one region. That region is called depletion region, so depletion region. In the depletion region, again this electron will move to this side and these holes will move to this side. Due to this movement of the charges, one current is generated that current is known as diffusion current.

And for forward bias, what happens, this positive terminal of the battery is connected to the positive side and negative terminal of the battery is connected to the negative side. So, what happens due to this, these positively charged holes will come this side and negatively charged electrons will come the side and this region will contract. So, under that condition, the charge will move, so maybe I can discuss in the next slides.

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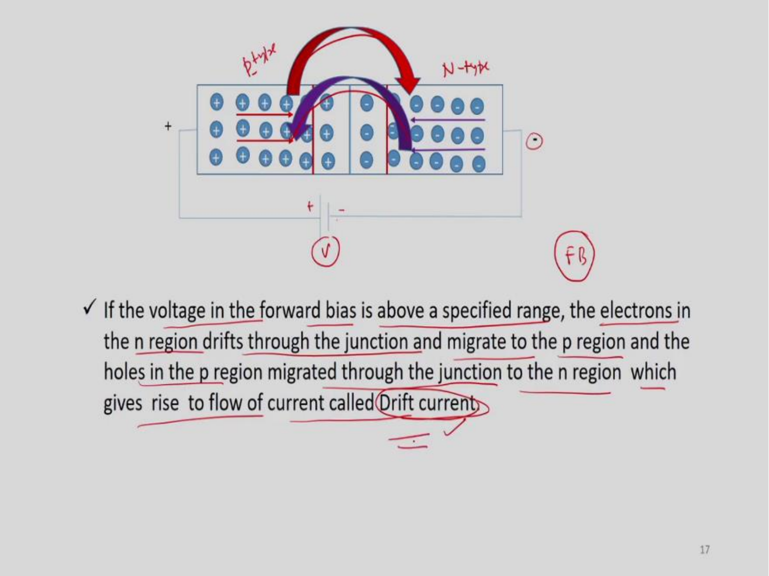

So, what happens, if this voltage, if the voltage in the forward bias is above the specified range, the electrons in the n-region drifts through the junction and migrates to the p-region. And the hole in the p-region migrate through the junction to the n-region, which gives rise to the flow of current called drift current. So, drift current is related to forward bias. Diffusion current is when there is no bias is there.

So, here, we have these are the positively charged holes and these are negatively charged electrons, positive terminal of the battery is connected to the positive side, negative terminal of the battery is connected to the negative side. And what happens here? It, depletion region is narrowed down. And then this electron will move from n-side and then holes will move to the p-side. So, this is n-type and this is p-type. So, this current, when this happens, this current flow through the circuit is known as the drift current.

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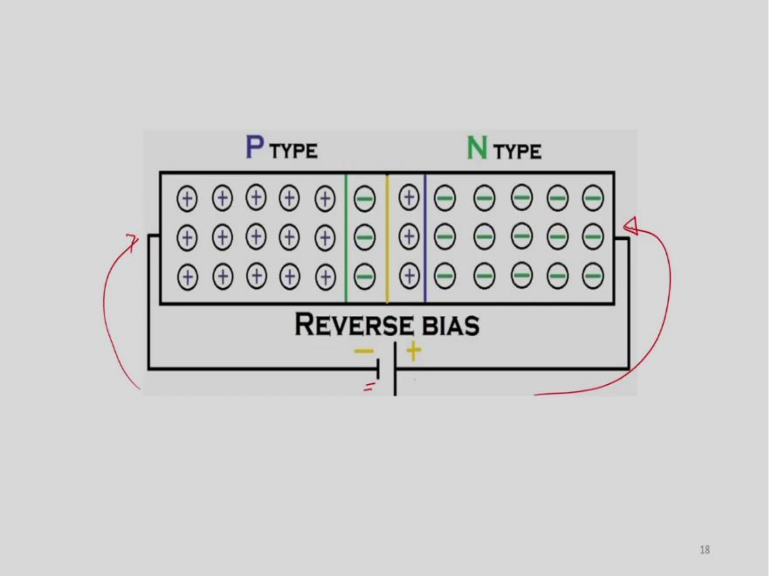

So, now, in case of reverse bias, what happens, this negative terminal of the battery is connected to the positive side and positive terminal of the battery is connected to the negative side. So, what happens here?

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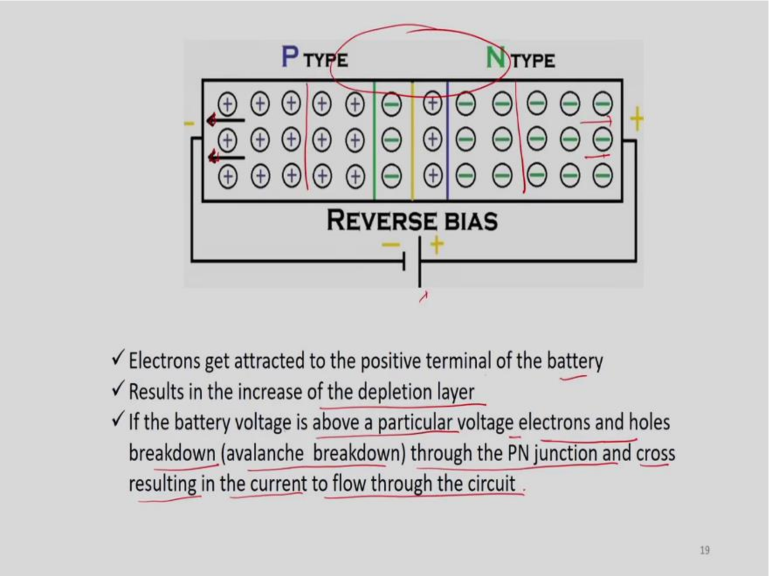

So, this will repel. So, because of this repel, so what happens, it extends this depletion region. So, it is very difficult to move now, the electron from this n-side to the p-side, and holes from p-side to the n-side. So, electrons get attracted to the positive terminal of the battery. This result in the increase in the depletion layer. If the battery voltage is above the particular voltage, the electrons and the holes breakdown, that is called avalanche breakdown through the p-n junction and cross resulting in the current to flow through the circuit.

So, what happens? This condition is now resemble like an insulation. So, if this is happens, if we further increase the voltage, then what will happen, so breakdown will occur. There is no p-n junction, this will melt or say diode, if we say, this will melt. This will no longer work. So, this is all about this semiconductor physics.

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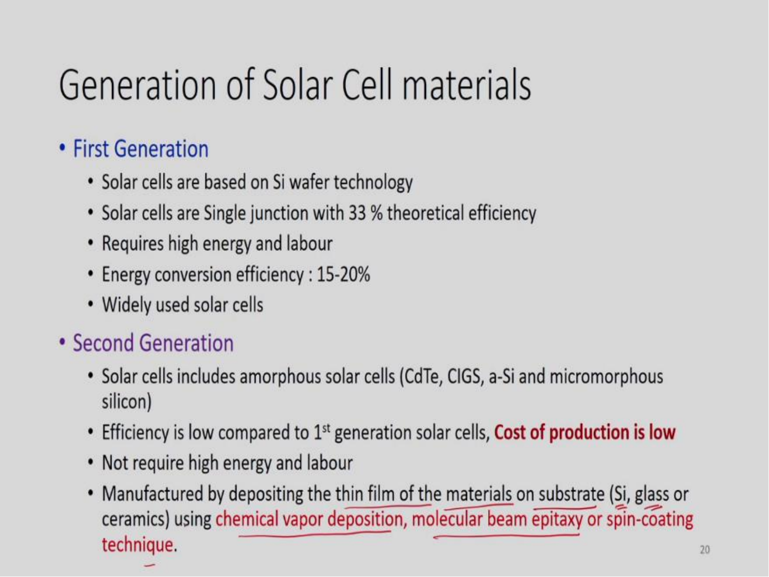

And let us now have some information about different generation of solar cell materials. So, there are three generations, first generation, second generation and third generation. In case of first generation solar cells, the solar cells are based on silicon wafer technology, what we have discussed. And solar cells are single junction with 33 % theoretical efficiency. And it requires high energy and labour as you can understand. So, we need a lot of equipments and that will work on very high temperature. And energy conversion efficiency is about 15-20 %. But, these kind of solar cells are widely used, in many of the applications.

In second generation solar cells, amorphous solar cells are included like cadmium telluride and then micro amorphous silicon, that kind of cells are included. But efficiency is very very low compared to first generation solar cells. But cost of production is also very very low. So, it requires less energy and labour. And this is manufactured by depositing the thin film of materials on substrates. That substrates maybe silicon, maybe glass or ceramics. And there are different techniques used among them, chemical vapor deposition, molecular beam epoxy or spin-coatings are prominent and people have used extensively these methods.

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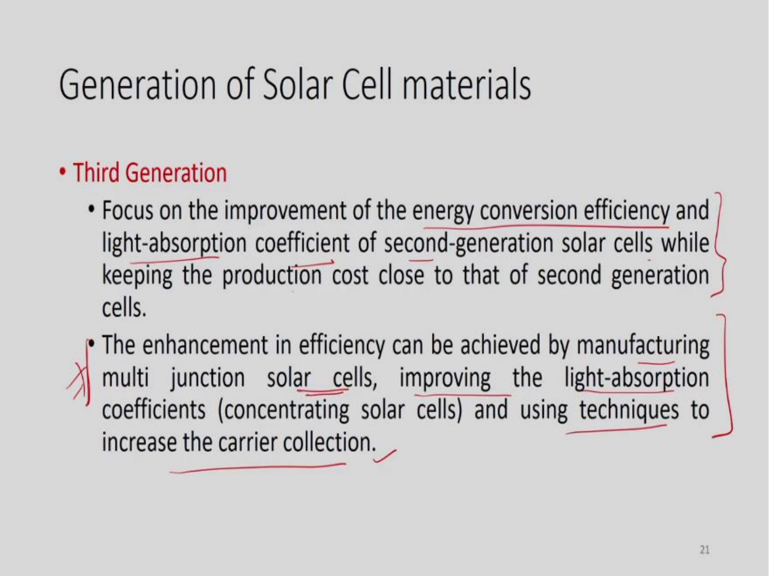

So, if we talk about third generation solar cells, which are the current generation solar cells, which primary focus on improvement of energy conversion efficiency and light absorption coefficient of second generation solar cells, while keeping the production cost close to that of the second generation cost. So, by maintaining the production cost constant, as far the second generation solar cell, but conversion efficiency should be higher.

The enhancement in efficiency can be achieved by manufacturing of multi junction solar cell, as we have discussed in the last class. So, multi junction solar cells are having higher conversion efficiencies. So, this is the option of increasing the conversion efficiency, and improving the light absorption coefficient by doing concentration or concentrating the solar cells and using techniques to increase the carrier collections. So, these are the third generation solar cells. So, these are primarily emphasized in the current times.

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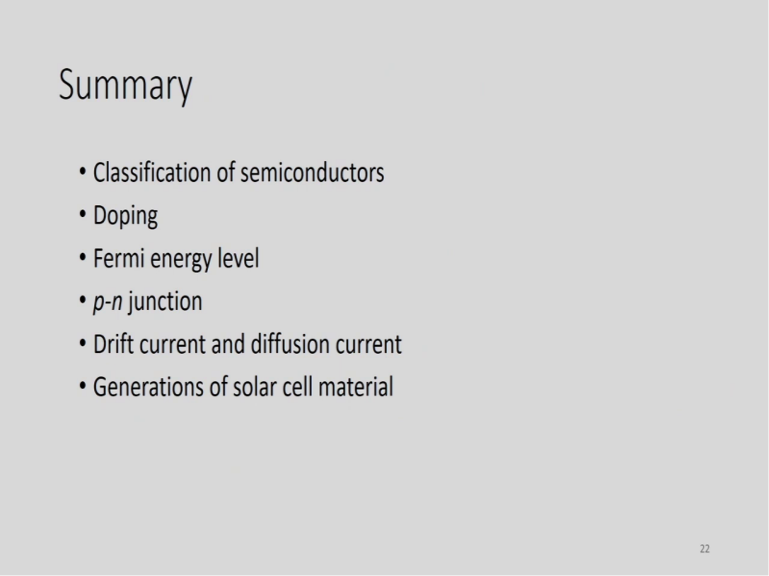

So, now, let us summarize what we have discussed today. We have discussed about classifications of semiconductors. What is intrinsic semiconductor, what is extrinsic semiconductor, what is doping, what is dopant, what is Fermi energy level, then p-n junction, what is drift current, what is diffusion current, and generations of solar cell materials. So, we have studied many more terminologies today, starting from conductor, semiconductor, insulator and we gave some examples of conductor, semiconductor and then insulators. And what kind of dopants are used for p-type, and what kind of dopants are used for n-type, what is acceptors, what is donors, what is free electrons, what is free holes? And finally, we have studied the trend of production of solar cells and what is going on in the current scenario and what needs to be improved for increasing the conversion efficiency.

So, thank you very much for watching this video.