Non-conventional Energy Resources
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Lecture – 14
Solar Energy: The p-n junction

In the last class we looked at the semiconductor in sort of in isolation, in particular we try to understand quite a bit about the band diagram. In particular I told you that we have something called the flat band diagram, and on most occasions that is adequate for us, it adequately explains to us how the behavior of the semiconductor happens and what are the you know steps that are involved in that process etcetera; these are all reasonably well captured by the flat band diagram, and that's the kind of notation that you most commonly see.

But at the same time I also told you that if you go dwell deeper into the subject, you understand that that flat band diagram comes from something more fundamental which is the e versus k diagram, which tells you the kinds of energy that the electron can have as a function of the you know wave vectors that it can have, and also we looked at you know how does that e versus k relationship interact with the periodic structure of the material and the fact that you see this band structure appearing because of this interaction of the e versus k of the electrons, with the periodic structure of that material.

So, this interaction is what creates situation where there is a diffraction occurring at specific locations, and due to diffraction there are some standing waves in those locations that creates a situation that is unfavorable and creates a gap in the energy. So, this distortion of the e versus k creates some values of energy, that are not allowed for the electron and that is what shows up as our band gap that we see. And that is how the band structure develops and that's how the flat band diagram relates to the e versus k diagram and the periodic structure of the matter. So, this is the background that we had, in this class we will build on it we will again start a little bit with these isolated semiconductors and then particularly we will focus on the p-n junction which is this particular concept that comes that can be put together when you put together specific type of semiconductors.

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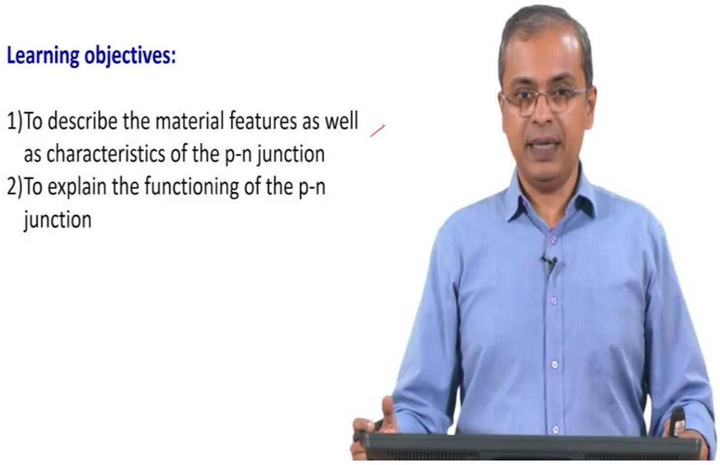

Learning objectives:

1) To describe the material features as well as characteristics of the p-n junction
2) To explain the functioning of the p-n junction

So, that is the focus of this class. So, in particular our learning objectives for this class are to describe some material features associated with this p-n junction as well as the characteristics of the p-n junction.

So, that is something that we will see running through the class at different points in time you will see references to this, and we will also look at trying to explain the functioning of the p-n junction. So, these are the 2 major points that we will look at of course, there is going to be a lot of detail as we go along, but this is essentially what we are trying to go over in this class.

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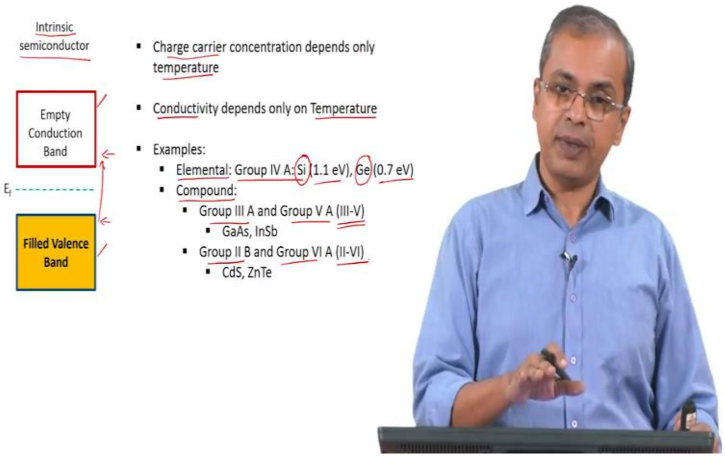

- Charge carrier concentration depends only temperature
- Conductivity depends only on Temperature
- Examples:
  - Elemental: Group IV A: Si (1.1 eV), Ge (0.7 eV)
  - Compound:
    - Group III A and Group V A (III-V)
      - GaAs, InSb
    - Group II B and Group VI A (II-VI)
      - CdS, ZnTe

Okay so we will begin again with the intrinsic semiconductor because that is it is the right kind of stage for what we are trying to discuss. So, as you can see on your screen there is an empty conduction band, and there is a filled valence band and so, that is the starting point for an intrinsic semiconductor; by definition an intrinsic semiconductor basically means that it is pure it doesn’t have any impurity in it, and most specifically it’s conductivity or charge carrier concentration depends only on temperature. What we mean by that is you have to have enough energy in the form of which is being provided in this case in the form of temperature, and at that point you will have some transitions from the filled valence band to the empty conduction band. And it is only these temperature induced transitions, that create the charge carriers in the conduction band ok as well as the empty holes that remain in the valence band.

So, that combination that gets created happens only as a direct result of the energy being provided into the system in the form of thermal energy. There is nothing else that is contributing to this charge carrier process. So, if you keep it at say 0 Kelvin or very close to 0 Kelvin, there will be no charge carriers and nothing you will not be able to see any significant electrical property from this material. So, charge carrier concentration depends only on temperature and as a result conductivity which depends first of all on the availability of charge carriers also it depends only on temperature okay. So, if there are no charge carriers there is going to be no conductivity. So, the first requirement for conductivity you have to have something that you can carry the charge, that is the thing that you are measuring and then referring to it as conductivity. So, if there is no charge carriers there is no conductivity, if you increase the number of charge carriers everything else being the same conductivity will go up.

So, if the charge carrier concentration depends on temperature, conductivity will also depend on temperature. More specifically if the charge carrier concentration increases with temperature conductivity increases with temperature okay. So in fact, that's also a very important characteristic of a semiconductor material as opposed to say a metallic system. So, we will talk about that very briefly as we proceed forward. So, examples of these intrinsic semiconductors are typically group 4 A elements. So, silicon and germanium are commonly coated as these intrinsic semiconductors.

So, they can actually be you can be intrinsic, the semiconductor can be intrinsic both in the form of an elemental version as well as a compound version. So, the elemental version is this idea that we can use silicon or we can use germanium for example, and they would have these specific band gaps of a 1.1 electron volt or 0.7 electron volts. But you could also have compound semiconductors where you actually have 2 elements, but they are in equi molar ratio. So, it is not really a doping kind of a situation, you have a group 3 A and a group 5 A element.

If you combine the 2 of them, again on balance they behave as though they were you know in terms of the number of electrons that are available in the system and so on, it looks somewhat analogous to a group 4 A element alone being present there and so, these are referred to as 3-5 compounds. So, that is the other way in which you can arrive at a intrinsic semiconductor, you could also do group 2 B and group 4 A combinations.

So, example would be cadmium sulfide or zinc telluride, and that would be referred to as a group I mean as a group as a 2 6 compound. So, group 2 b and group 6 A. So, this combination is referred to as a 2 6 compound. Notionally you can actually consider even going further in the periodic table away from group 4 group 4 A, but then increasingly you are increasing the chances that the bond formed will be an ionic bond, because there is going to be that much difference in the electron affinity and electronegativity of the 2 elements involved.

So, generally we are looking at only at these group 4 A as elemental semi intrinsic semiconductors or 3 5 compounds or 2 6 compounds as elemental as compound intrinsic semiconductors. So, this is the general set of characteristics associated with an intrinsic semiconductor. Now if you take an intrinsic semiconductor and to that you do add something called a Dopant. So, that you create something called as an extrinsic semiconductor.

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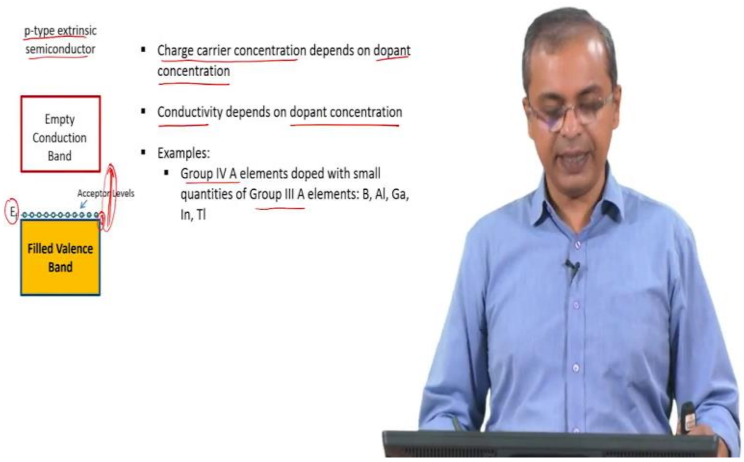

p-type extrinsic semiconductor

- Charge carrier concentration depends on dopant concentration
- Conductivity depends on dopant concentration
- Examples:
  - Group IV A elements doped with small quantities of Group III A elements: B, Al, Ga, In, Tl

So, that is what we are discussing here, we can again have that in 2 forms we have something called as a p-type extrinsic semiconductor, in which case you create this is arrived right by you know starting with a group 4 A element. So, for example silicon, silicon is the most commonly used element in this case, because you already have an industry which is using silicon based single crystals, which is all the electronic industry that you have and in this you can dope small quantities of group 3 A elements.

So, those would be boron, aluminum, gallium, indium, thallium. So, these are all elements in the which are group 3 A elements, and you could dope a little bit of this into the silicon structure. So, what happens is that these are elements that are you know they have one valence electron less, than that of silicon and so, they are potentially in a capable of grabbing onto an electron or in other words releasing that vacant location. So, that releasing of that vacant location is referred to as a hole. So so, they have acceptor levels they can accept those electrons very easily, and those acceptor levels are just above the valence band. So, whereas, in a intrinsic semiconductor the Fermi energy level is right in the middle halfway between the valence band and the conduction band. In in the case of an p-type extrinsic semiconductor, it essentially lines up with the acceptor levels because that is where the essentially the action is, and as I said the Fermi energy is the indicative of the chemical potential of the electrons in the system, and this is a very representative of that in that case. So, so you have this situation where you have this acceptor levels that are very close to the Fermi energy levels.

So, this changes the behavior of the semiconductor quite dramatically. The change actually appears in the idea that now the charge carrier concentration is not solely dependent on temperature in fact, at room temperature it is not dependent on temperature for a very wide range of temperatures it is not dependent on temperature.

It is not a it's not a uniform behavior, what happens is that extremely low temperatures it is dependent on temperature, but then at even marginally some you know some relatively small amount away from say 0 Kelvin as you start increasing temperature, it pretty soon levels off the charge carrier concentration levels off and remains flat for a very long range of temperature. So, typically the all these semiconductors at room temperature have a constant charge carrier concentration. Again if you raise the temperature very significantly high, the charge carrier concentration begins to climb again, and that has got to do exactly with this band structure that you are seeing on your screen, and that is got to do with the fact that you need very little energy to do this jump from the filled valence band to those acceptor levels.

So, that happens at extremely small temperature, that small temperature itself is adequate energy to provide you this shift. Now once you have done that, and there is only a small number of you are only doing a small amount of doping. So, all those charge carriers and now have now become available for a very small increase in temperature. Beyond that for you to further increase the charge carrier concentration, you have to go to much higher temperature before this transition becomes possible.

So, as long as you are in the energy level between here and here in that entire intermediate range of energies and the corresponding temperatures, there is no change in charge carrier concentration, all of it comes only from this acceptor level related transition, you don't really see the intrinsic transition this find this transition. This overall transition that you see here would be referred to as the intrinsic transition. So, the intrinsic transition occurs only at much higher temperatures, you don't see that in this system at the lower temperatures. So, for a significant fraction of temperature range, you find that the charge carrier concentration depends only on the Dopant concentration, it doesn’t depend much on the temperature it is flat with respect to the temperature.

So, if you increase the Dopant concentration, then for that entire temperature range you will have a higher charge carrier concentration. If you decrease the Dopant concentration for the entire temperature range you will have lower charge carrier concentration. And again conductivity depends on the Dopant concentration, because it depends on the charge carrier concentration.

I told you in the earlier also fundamentally for conductivity to occur you need the charge carriers and so, charge carrier concentration directly reflects on the conductivity of the material, and since the charge carrier concentration is now independent of temperature and only dependent on Dopant concentration, the conductivity also follows the same trend and depends only on Dopant concentration. So, this is the p-type extensive semiconductor, and as I said it is simply consisting of group 4 A elements with the small group 3 A elements doped into it, small amounts of group 3 A elements doped with. You can think of an analogue a situation where you have the group 5 A elements being doped into the system, and that would create your n-type extrinsic semiconductor.

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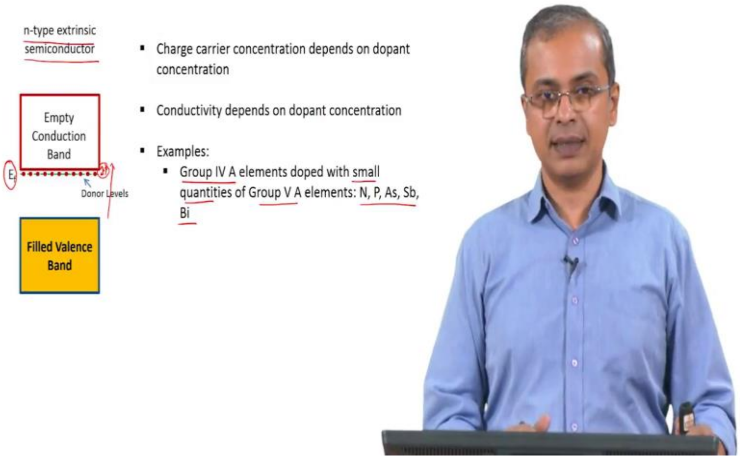

- Charge carrier concentration depends on dopant concentration
- Conductivity depends on dopant concentration
- Examples:
  - Group IV A elements doped with small quantities of Group V A elements: N, P, As, Sb, Bi

So, the n-type extrinsic semiconductor has conceptually is many similarities to the p-type except fundamentally the charge carrier is different here. Here you are essentially taking again the group 4 A element, that’s a good starting point for us again silicon is a very good starting point for us and in that we dope small quantities of group 5 A elements; those are things like nitrogen, phosphorus, arsenic, antimony and bismuth. So, those are the kinds of elements that we have available to us in group 5 A, which we can dope into a silicon and create the situation where you have n-type extrinsic semiconductor.

Now these elements have essentially one additional valence electron available to them, and so that valence electron is available for more free movement within the system and therefore, at very marginal availability of energy this electron begins to run around the system. And that is captured in the band diagram by this donor level, which stays very close to the conduction empty conduction band. So, at very small amount of energy you can get this donor electrons to get into the conduction band, and then carry out the conduction processes.

So, the electrical properties then get defined by this transition, which is occurring at extremely small energy. Once again you can still have an intrinsic transition, but that will occur at much higher levels of temperature, because you have to have corresponding energy to enable this huge transition huge gap has to be jumped. So, here again the Fermi energy now is lined up with this donor level and and so that is characteristic of this structure of the n-type extrinsic semiconductor. So, and again you know this is again consistent with the fact that, that’s where the energy level of the electrons is and therefore, effectively the chemical potential of those electrons is right.

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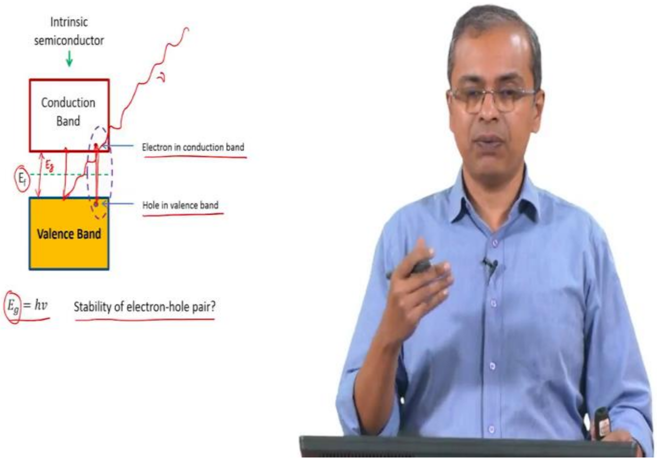

So, now if you step back and again look at the intrinsic semiconductor for a moment, we will use this for just to understand one important concept as to why we need in this class we are going to look at p-n junctions, we would like to first understand why we need to look at p-n junctions okay. So, in general we see that if you take a semiconductor in this case I am taking an intrinsic semiconductor to you know for the sake of clarity, so that we are not you know having too many parameters to keep in mind.

So, in an intrinsic semiconductor where you have a bandgap of E g, and a Fermi energy level E f okay. So, for this bandgap if you do E g equals h nu. So, you have some incoming radiation right if this has a nu and the frequency of that radiation is such that h nu corresponding to this radiation is equal to the band gap E g, then you can do this transition, and that’s what I have shown you here an electron caught transition from the valence band to the conduction band.

So, now, you have an electron sitting in the conduction band, and since it transition from the valence band you have a hole sitting in the valence band okay. So, this is what we have. So, in principle if you are if the idea of this use or this particular use of the semiconductor is simply to capture solar energy, in principle we are already said you have an intrinsic semiconductor you put it out in the sun you will have transitions, you will have transitions. So, solar energy has been captured by this material now so so in fact, we should essentially stop our discussion with this, there is really nothing more to look at if this is all there is, but we end up having to look at some additional parameters and particularly that leads us to a p-n junction specifically because of one particular issue.

The issue is that when you do this kind of a transition, the electron and the hole are pretty much right there they are in great proximity to each other. So, if you give them even a fraction of time, they will just collapse right back. So, the electron will fall right back because it is not sitting at the lowest energy level that it can possibly sit at. So, even though you send in the radiation and lifted it up to a higher energy level, if you give it some chance it will go back to it is lower energy level and close that valence close the hole in the valence band. So, it will recombine with that hole, and it will go back to it’s original location in the valence band.

So, what happens here? When you do this or when this happens in the material, you are not capturing the electricity; you are not the when this happens you no longer have that electron to go to the external circuit to do some job and therefore, effectively you have not generated electricity you did a transition, but you did not generate electricity. You did not capture the electricity in any manner that you could use for some particular application. So, what has actually happened is you created this electron hole pair and they recombined. So, they recombined. So, recombination is an event that happens in semiconductors, it is not something that you can completely eliminate it will happen, but we would like the semiconductor and devices based on the semiconductor to be made such that, despite the recombination you can still continue to do something useful with it right.

So, when you have single semiconductor sitting like this, that option becomes difficult for you; you are not really in a position to completely utilize this electron hole pair that you generated, it simply recombines and therefore, you have an issue effectively of this electron hole pair. So, the idea of not just stopping with this kind of a semiconductor, but creating a device based on it in this case a p-n junction, is atleast one of the reasons for it in from the perspective of solar energy capture. It is use p-n junctions are used for a variety of different things, from the perspective of solar energy capture one of the reasons we look at this is that the p-n junction will do something that will stabilize the electron hole pair. So, that part we will see as we go ahead in a in a little later, but now we will look at the p-n junction, we will try to understand what how it comes together what are some specific aspects associated with it.

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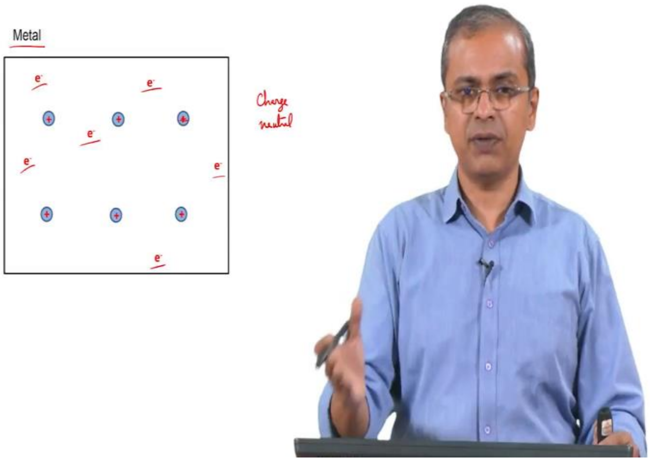

To get into this diagram that I am going to show you about a p-n junction, I would like to first start with a diagram that relates to a metal.

So, in a metal we one one image that we have of a metal a model that we have for a metal is that, you have all these positive ionic cores positively charged ionic cores, which are in a crystalline position they are holding some crystalline locations inside a crystal structure and then you have a sea of electrons. So, you have electrons roaming around. So, when it when this happens the overall material is charged neutral. So, overall material is charged neutral. So , material is charged neutral.

So, there is no specific charge that it has built up, the electrons are free to roam around and the ionic cores are fixed. So, we have this idea of fixed ionic cores and a sea of electrons. So, that is an image that we have of a metallic system, but to keep in mind the entire metallic sample from one end to the other, is actually charge neutral. And therefore, even though the electrons are free to roam around the entire structure the overall structure continues to remain charge neutral. And to the extent that you are not putting a potential on this or a doing any such thing, it and that it’s only sitting as out there as and experiencing the temperature of the system of the surroundings.

Then these electrons are roughly equally distributed throughout the metallic sample okay, and that’s how the overall charge neutrality is maintained and relatively you know even section by section if you look at various locations in the metal, by and large the charge neutrality is going to be maintained. So, that is how a metallic system behaves. So, we will keep this in mind we are now going to look at a semiconducting system we will have some diagrams relative to the semiconductors, and I will at least alert you to specific aspects which may have some similarity to this, but will be in many ways different.

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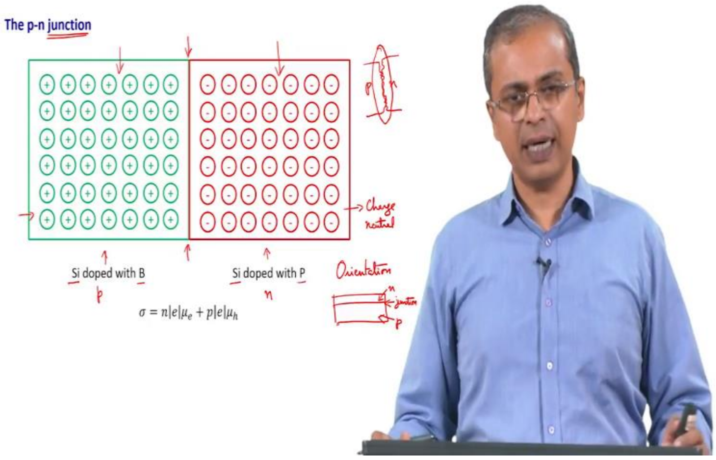
The p-n junction

Si doped with B

Si doped with P

$$\sigma = n|e|\mu_e + p|e|\mu_h$$

So, here we have a p-n junction. So, we will start our discussion on the p-n junction with this image here. So, what do we have, as we saw we you can get a p-type semiconductor by taking silicon and doping it with 3 A group of elements. So, in this case for example, I am just saying that we are doping it with boron, which is in the 3 A group of elements and then. So, that is this side; that is this side of this sample which I have colored green for easy identification on our right side we have silicon again silicon, and it is now doped with phosphorus which is a group 5 A group 5 A element. So, this is what we have done and. So, this side is p and this side is n, p-type semiconductor is on our left side and n-type semiconductor is on our right side.

Now even before I proceed further on this one fundamental material aspect I should alert you to and that is that when we speak of a p-n junction. So, clearly there are 3 things here there is a p material there is an n material and there is a junction. So, that is the point that we should keep in mind, and it is a very important point to keep in mind that junction is essentially here okay. So, that junction is here now the junction is a very important part of this unit the p-n junction. So, when I say important the point that we have to keep in mind is that notionally you can actually take a p material that is separately made, and an n material that is separately made and then you can bring them together okay and then press them against each other. When you do that you do have a p material, you do have an n material and at the place where they have come in contact you have tried to create a junction. Now that junction is highly imperfect at an atomic level okay, because a surface even though it looks you may polish it and it looks very nice and shiny when you look at it, if you actually look at it under the microscope at the atomic level it is extremely rough it is up and down in all different ways.

So, you will have a junction where let's say you have a sample that looks some surface that looks like that and another surface that also looks like that. So, then you will have. So, let's say this is p and this is n, then you have a region here which looks like the junction or where you have tried to create the junction, but that junction is extremely poor. You find lot of gaps here that will plenty of gaps in that junction so in fact, the junction actually exists only on specific points, where those 2 materials are in very good contact at an atomic level.

For the rest of it the junction even though apparently it is there for us in from a visible from our eye perspective the resolution of our eye perspective, in reality it doesn't exist and we will actually have extremely poor characteristics it will try to mimic the characteristics that we are going to describe here in this class. But it will do a poor job of mimicking those characteristics, primarily because the junction is in a very poor state okay. So, it is very important to keep that in mind and so, even though we conceptually talk of a p material and an n material and n junction, and it may become easy to think of it as 2 separate materials that have been put together even descriptively when we are trying to understand their behavior, it may make sense to describe it that way.

In reality if that's the way in which you make it, it will do a poor job of functioning so. In fact, what they actually do is they take say a single crystal of silicon and then in that same sample. So, it is already a single crystal, there is no boundary in it, there is no grain boundary in it, it's a single crystal of silicon we dope it from one side with the p-type of dopant, and we dope it from the other side with the n-type of dopant. Those dopants diffuse and in the middle they form a boundary. So, at this point you create a p-n junction, where you have already got atomic level contact atomic level order and therefore, the junction is very well defined. And so, this junction if you build it that way is very well defined okay. So, that’s a very important part of this p-n junction coming together to create a p-n junction. The other thing I will alert you to 2 more points that I think are very important before we move forward from this graph from this plot or the schematic, is that on your left hand side I have put a lot of positive signs here okay. So, lot of plus plus plus I have put on the left side, and minus minus minus on the right side. So, I think we have to take a step back and understand what exactly we have done here. I want to alert you to the fact that this does not mean that the p side is positively charged, and the n side is negatively charged that is not the case.

The p side is independently charged neutral, the n side is independently charged neutral. So, both these materials are actually charge neutral, both these sides that you see are charge neutral okay. So, both are charge neutral both this side as well as this side, they are essentially charge neutral because what you have done is you have taken silicon and you have doped it with boron. So, silicon has the same number of equal number of protons and electrons, and it is being doped which means specific silicon atoms are being replaced by boron atoms, which are also having an equal number of protons and electrons.

The number of protons and electrons in boron will be not less than that in silicon and so they will that will be different, but within boron the number of protons and electrons is the same corresponding to it’s atomic number, and again within silicon the number of protons and electrons is the same correct corresponding to it’s atomic number. So, given this situation over all these silicon doped with boron is going to be charge neutral, there is not going to be any either deficit of electrons or excess of electrons that is not going to be there.

Similarly, when you take silicon and dope it with phosphorus, even though phosphorus actually has one extra valence electron overall it has the same number of protons as it has electrons and therefore, phosphorus by itself is charge neutral, and you are using it to replace silicon atom which is also charge neutral and therefore, the overall silicon doped with phosphorus continues to be charge neutral. So, what is the meaning of putting these minus signs and plus signs? In that sense this is similar to what we are discussing here in a metal, where we basically said that you can have some free electrons that are moving around. So, this charge carrier we have indicated with a sign here. So, similarly here you can think of the p-n junction, the p side of the material to be consisting of a material where in the bond structure you are short of one electron and therefore, it is ready to accept an electron from somewhere okay. So, it is ready to accept an electron from somewhere, and effectively release this lack of electron there or release this hole. And so, this ability to release that hole is what we are saying, what we are referring to by is indicating that it is it has the ability to release these positive charges or essentially the positively charged holes. The same way same thing would be true with the n side of this material, it is essentially charged neutral, but the if you look at the bonds that are present there, it essentially has one additional because the phosphorus has one additional valence electron, that valence electron is easy to release and is ready to move around the system.

So, when you create this material this n-type semiconductor, you actually have all the ionic cores sitting around and you have this free electron running running through that material. You can think of it that way at room temperature, it is in a position to do that. Similarly on the p side it is equivalent of saying that you have this relatively neutral material, in which you have actually this negatively charged ions sitting at some location, with this positive set of charge carriers that are running uniformly throughout that system at very low with very little amount of energy.

So, the positive that you see here are the availability of those positive charge carriers that can move across. So, that is the positive that you see here, and the negative that you see here is the availability of those electrons on this side which can move anywhere if they are given the opportunity. So, that is what we are referring to as this p-n junction, and what we are referring to here is the signs that you see there I will also point out that one additional aspect you should keep in mind is the orientation of this sample. So, throughout this class we will sort of stick to this horizontal orientation. So, you are going to see the p on your left hand side, and n on your right hand side.

So, many diagrams the few diagrams that you are going to see here are all going to follow this kind of a layout. When you actually use it as a solar cell, this is not the orientation in which it will sit, it will sort of be 90 degrees at the other way. So, you are actually going to have one type of semiconductor on top, and another type of semiconductor of the bottom and the junction is going to be in the middle. So, you are actually going to have something like this and you will have a junction okay. So, this will be the junction, this will be your let's say the n-type and this will be the p type okay. So, this is junction. So, in a solar cell the orientation is the other way, it is not the way you are seeing in the screen or as you will see through the rest of the slides that you will see in this class, in any case when we talk about solar cells as we come up to that discussion I will again alert you to it. So, some of the diagrams we will draw here you have to at least visually in your mind imagine them to be turned rotated at 90 degrees vertically, and then you can understand how it relates to what is going on in solar cell.

So, anyway. So, this is the diagram; now starting here we will add some more detail. So, what happens is once you bring these 2 together once you bring this p-n junction together initially it looks something like this. So, all the you know positive holes which are sitting on the p side which are freely roaming around on the free side are on the p side, and you can think of it that way conceptually, and then on the n side you have all these electrons that are freely roaming around. But once you know create the situation where conceptually you suddenly brought them together, like I said that is not how it happens you build it that way, but let's say you brought it together and you created this situation.

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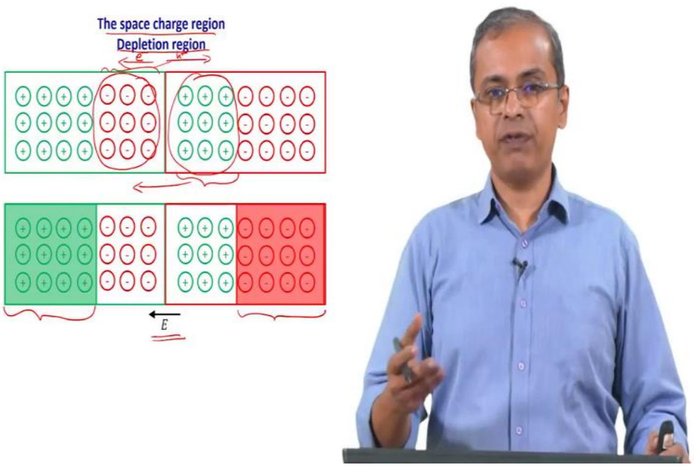

What happens is from a material perspective the electrons suddenly have a access to the entire sample okay. So, although originally they started off only here the electrons, and now notionally they have this I mean they have access at least physical access is there to this entire extent of the sample, I mean there is a sample ahead of them and given that they are freely roaming around, and there is thermal energy available to them they are free to actually try to access that volume as well.

So, they will start diffusing so they start diffusing into a region which is different from the region from where they originated, all right. So, this happens, and that is how some of these electrons are now have moved into this region. So, electrons have moved this way, I started they started off in the n region and they moved into the p region. Similarly the holes which were freely roaming around in the you know p side of the sample, suddenly get access they see that there is space available on the n side of the sample and they start roaming into that region. So, you have holes moving the same.

So, I will put as h plus. So, what happened? These electrons and holes came from a region that was close to this. So, I will just remove this mark here and we will get back to it. So, this electrons came from a region that were that was relatively close to the boundary and then these are the electrons that moved across. Similarly the holes also came from a region that was relatively close to the boundary and these are the holes that moved across okay. So, in a region close to the boundary or close to the junction, you are suddenly short or you are missing holes on the p side of the sample, and you are missing electrons on the n side of the sample, because they started they started diffusing into each other all right.

The the ionic cores itself that is the silicon atoms as well as the boron atoms or the phosphorus atoms that are present, they are not moving at room temperature at room temperature that is not we don’t have sufficient energy to break the bonds, these are all covalent bonds to break those bonds and to get those atoms to diffuse across, there will be some minuscule diffusion, but that is that will be completely negligible in this scale. So, but in general they are going to just stay stuck.

So, the core structure which is the p structure as well as the n structure we will remain, that basic framework will remain the p structure will remain on our left hand side and the n structure will remain on our right hand side. So, that basic structural remain, only the charge carriers suddenly have this freedom they start moving and so, suddenly on the n side we have lost some electrons because they went off into the p side, and on the p side we have lost some holes which have gone on to the n side. As a result the there is a variation in the charge you suddenly see on the p side of the sample negative charge building up, and on the n side of the sample positive charge building up okay and so, that is what I have sort of indicated by the fact that you know with this movement of charge, you are suddenly having positive charges sitting here because the electrons left that place and negative charges sitting here because the holes left that place right. So, originally those 2 regions were completely neutral, but suddenly now you have this situation, where there is a charge that has been built up.

So, that is why when you create a p-n junction, we and this situation begins to build, we refer to this as the space charge region okay. So, that is this is one term that is used it is called a space charge region. So, this is the region of space inside that material, where a charge buildup has been created. It is also referred to as a depletion region, because the majority charge carriers in each side of the junction have been lost. So, they have been depleted on the n side the electrons were the majority charge carriers they left that region and so, you have been depleted of electrons, on the p side holes where the majority charge carrier they also left that region and therefore, you have been depleted of holes.

So, that is why it is also referred to as the depletion region. So, if you look at the diagram below, I essentially taken the same thing as what is above just and highlighted the fact that this continues to remain charge neutral this also continues to remain charge neutral. So, this effect is limited to some region, and it is a relatively sharply defined region because they start diffusing and then it comes to a halt why does it come to a halt and why doesn’t this continue indefinitely? It has got to do with the fact that the electrons and the holes are charged particles right and the framework from which they arrive start off with, is an oppositely charged framework right.

So, whereas, in a metal in the sample in the original example that we looked at, all the ions the ionic core from one end of the sample to the other end of the sample the entire ionic core is all uniformly positively charged, and the electrons are uniformly negatively charged therefore, the electrons can go from one end to the other and nothing happens it’s all charged neutral. Here in a p-n junction, the ionic cores, if you keep aside the charge carriers if you detach the charge carriers if you look at the ionic cores the ionic cores are going to be positive on the n side and negative on the p side.

So, therefore, it is the same ionic core is not there from n to n, it’s a different ionic core on either side of that junction therefore, the electrons cannot freely roam everywhere in the sample because they see a different ionic core on one side of the junction, relative to the other side of junction and so, as they move it is no longer being charged neutral you are building up within the sample and. So, charges built up and therefore, a field is built up electric field E, which goes from the positive charge to the negative charge, because this field is there it begins to oppose the flow of further flow of electrons or holes ok.

So, it this field is building up it is now trying to prevent further buildup of the field and and so, as the diffusion process continues slowly the diffusion process begins to slow down because the electrons are forced to now go up this barrier and they are unable to do. So, because already some electrons have gone and that repulsion is now sending them back. So, you have electrons moving due to diffusion which is a thermal process.

So, they are continuing to do so as much as possible, because they just randomly moving around including across the junction, and then because the build there has been a field built up some of the electrons are being sent back, if you want to look at this discussion from the perspective of electrons. So, some of the electrons are being sent back. So, the field sends back electrons and the diffusion sends the electrons forward, diffusion tries to push the electrons from the n side across the junction into the p side, the field pushes the electrons from the p side back into the n side across the junction. So, when the 2 rates reach an equilibrium, you arrive at this structure that you see which is the p-n junction with it’s depletion region or space charge region.

So, that is the manner in which this junction behaves after it has been created. I would also add that in this figure the way we have drawn it, and in many of the figures that we will see you would see a sense of symmetry here. In the sense that whatever I am showing you on the left hand side of your image, I am giving you an analogous image on the right hand side of the image, but it is not necessary that it has to be symmetric the way I have shown you.

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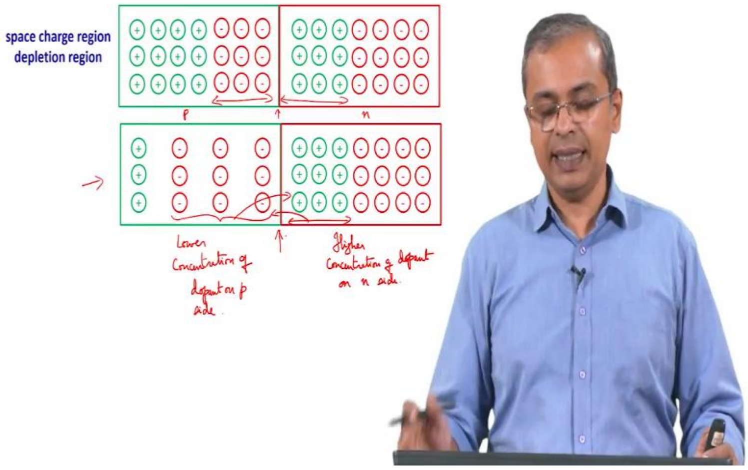

space charge region
depletion region

So, for example, I can have space charge region and depletion or the depletion region looking very asymmetric across the boundary. So, if you look at the top figure here, the region is symmetric on both sides, you see the same extent of the region on both sides of this junction right that is because the p-type material and the n-type material were in this sample, in this example that we have been discussing although we didn’t explicitly say it and now I am going to say that explicitly the p-type sample as well as the n-type sample which came together for this p-n junction both of them were doped to the same level or in other words the doping concentration on the p side of the sample, was the same has the doping concentration on the n side of the sample.

That is the reason why the concentration of charges on or the concentration of charges or the concentration of the availability of those charge carriers and charge carrier concentration is the same on both sides. And if it is same on both sides then you see this symmetric behavior. Then for some number of electrons that cross over, since charge overall charge neutrality is there you will have a same number of holes cross over to the other side and you will also have the region over which the holes come and the region over which the electrons come being similar okay because the doping concentration is the same. So, if you are going to access you know one million Dopant atoms for example, you have to go to the same depth on the n side of the junction, as you have to go to the p side of the junction to get one million charge carriers on either side of the junction. So, that is how it happens if the Dopant concentration is the same. Supposing on the other hand as you see in the sample below the this is doped to a less lower concentration and you have a higher concentration. So, when you have a higher concentration of Dopant on the n side, to get the same number of charge carriers you have to go to a certain depth to get those charge carriers and then send them across to this side. But on the p side because you are now having a lower concentration you have to go much deeper into the sample to get the same number of charge carriers and send them across right.

So, therefore, it is important to understand this, that it is not necessary for this p-n junction to be you know symmetric or this charge space charge region to be symmetric across the junction, it does not have to be and it often is not. And in fact, we may even find it interesting and useful for us to deliberately create a situation where they are not equally in equal degrees on either side of that sample okay.

So, this is something that we should keep in mind, I have just shown you an example where the p side the Dopant concentration is less, and the n side the Dopant concentration is more, you can similarly think of a situation where let’s say on the p side the Dopant concentration is high, whereas, on the n side the Dopant concentration is low. So, again here you are going to a much greater depth then you are going here okay. So, to do this you know to do this transfer. So, this is something that is worth remembering and keeping in mind and as necessary we will utilize it.

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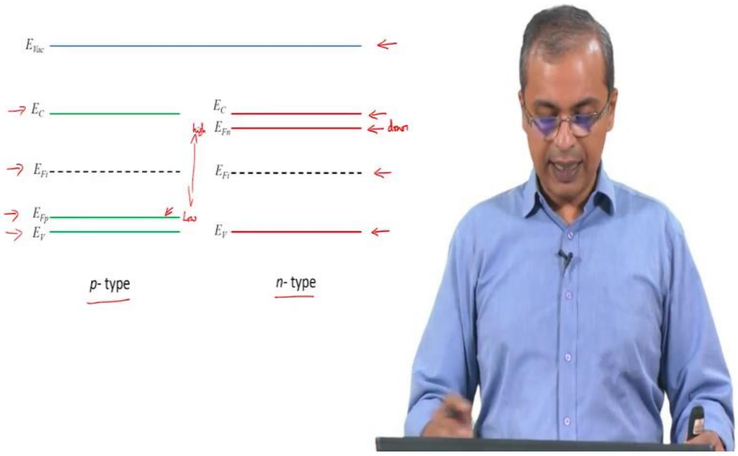

Now, we will also look a little bit on the energy of this system and the various energy levels that are involved here. So, in both these samples, because you are starting with silicon as our starting point, we have the valence band, the top of the valence band that is sitting here and we have the bottom of the conduction band.

So, on both sides I am just showing you notionally some aside that is the p side and an another which is the n side, and we are looking at a situation where we are just about to bring these 2 together to form the junction okay. So, we are going to see what is happening to the energy levels in the system as we start off with these 2 independent materials and bring them together to form the junction. We just now we saw what happens conceptually in terms of charge carriers moving on either side, we would like to also understand what is happening with respect to these energy levels.

So, we have 2 important levels that I have already drawn your attention to the conduction band and the valence band, there as. If the material were intrinsic then the Fermi energy would be this the intrinsic Fermi energy of this silicon sample. So, that intrinsic value is going to be the same on both sides of this boundary, because that is the original value of that material. But now that you have doped the material that is not the Fermi energy, that is of that is operational. So, to speak in the system the system the energy that level that is operational is this Fermi energy E f subscript p which is the which means it is the Fermi energy on the p side of the sample, and you have here E F n which is the Fermi energy on the n side of the sample.

So, these are the 2 values that are of greater interest as I said, this is now this is closer to the Dopant or donor level energy level. So, this is the donor energy related Fermi energy and this is from the acceptor level. So, that is basically what we have of course, the vacuum energy level is sitting up there, and I mean it is something that is that basically sets the 0. So, to speak and everything else is below that okay. So, that is the way we would look at it.

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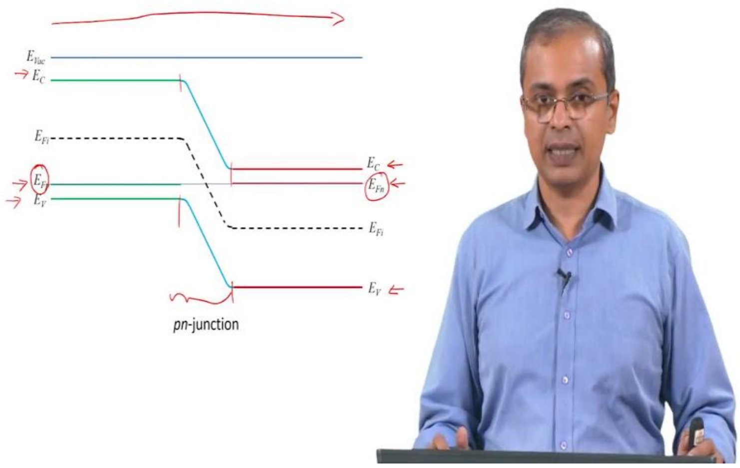

So, now, let’s say we bring these materials together and what we will see is that the main concept that happens when you do this bring these materials together is that, the Fermi energies on either side begin to line up with each other. Because they represent the highest energy level that the electrons can have and is essentially they are the chemical potential correspond to the chemical potential of the electrons in the system, and therefore, they cannot you cannot have you cannot at equilibrium have a situation where the chemical potential is different in different locations in the sample. That is the driving force there any difference in chemical potential is the driving force for a process to occur and you end up creating in equilibrium only when the chemical potential becomes even across the sample.

So, the 2 samples the energy levels in the 2 samples rearrange themselves. So, that you get the situation, where the Fermi energy now is uniform across the sample whereas, previously this Fermi energy was low, and this Fermi energy was high relatively speaking relatively speaking right the E F n was high E F p was low. So, clearly when you move the entire thing on the left hand side up, and the entire thing on the right hand side down till the Fermi energies line up everything else will also shift you all your conduction bands will shift valence bands will shift etcetera. So, if you go back here.

So, if you again look in isolation to the left hand side of your sample, you will see the energy corresponding to the conduction band on the p side of the sample, the energy content corresponding to the valence band on the p side of the sample, and the Fermi energy corresponding to the p side. Independently you can again look at conduction band energy level on the n side, valence band energy level on the n side and the Fermi energy level on the n side. But they have now repositioned themselves, I mean on the n side they are all the same, on the p side they are all the same as you saw in the previous plot, but relative to each other they have repositioned themselves such that, the Fermi energy on both sides is the same value is now at the same level ok.

So, this creates a situation where the conduction band energy level is forced to now vary over a region that is that I am marking here. So, the conduction band value is a little high high on the left hand side of our image, as you continue from the left to the right as you move from left to right you find that the conduction band energy level is high, and then it steadily and at some point as it comes close to this junction, it begins to go down and then it reaches the conduction band energy value of the n side of the sample, same thing about the valence band.

It starts off at a high value and then as you go towards the right hand side, it will reach a point close to the junction where it starts sliding down, and then it reaches the value of the valence band energy level of the n-type sample and then it stays at that value through the sample. So, this in between region that you have, where you have this band energy value changing from one value to the one level to the other level is referred to as the region where the band is bending okay. So, band is bending in this region, and it is very interesting for us to keep in mind because this is a very key parameter in deciding how the p-n junction behaves, when it is used as a for a solar cell application. And incidentally if you just for notionally if you follow the value of the Fermi energy of your intrinsic sample, then the region where it crosses the Fermi energy of this you know p-type n-type, a combination, that location is essentially where the p-n junction boundary is okay. So, the p-n junction boundary is at that location and that is how you see it, the and that’s how we determine what the location of that p-n junction boundary is fine.

So, this is how you look at the energy values as you combine a p-n junction, I have of course, done some color coding here just so, you understand how this system is looking when you go from left to right, there is no other significance to the color coding. The conduction band value is one uniform value, which moves from a high value to a low value as you go from left to right, valence band energy value also goes from a high value to a low value as you go from left to right, the Fermi energy level remains flat as you go from left to right. So, that is really the only significance of those lines, the coloring is simply to show you the different regions that exists as you go from left to right.

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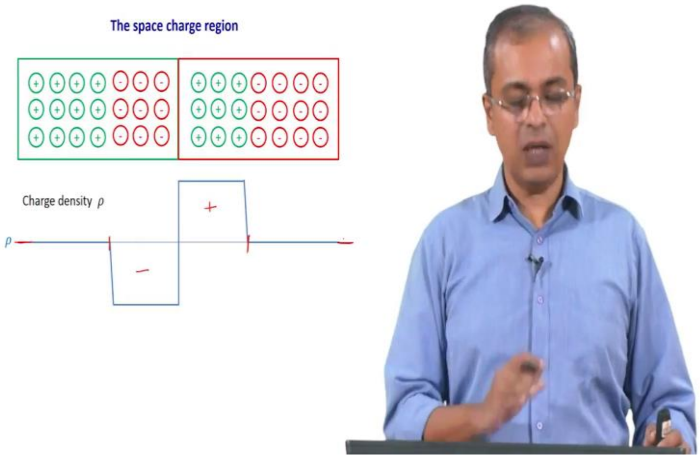

The space charge region

Okay so just a few more points to keep in mind in this space charged region and this relate to how this sample behaves as you utilize it. On the generally the if you look at the charge density that is created as a function of position, you will see if you start from the left hand side of this image it is charge neutral and therefore, this is you can set this as the 0 level. So, this is the 0 zero level. So, it is the charge neutral material and as you move towards the junction as you arrive at the space charge region relatively sharp transition is there and you get this collection of negative charge right.

This is a p-type material the holes have left. So, the and electrons have moved in and. So, you have a negative charge there. So, you have a charge buildup which is negative in charge and then as you cross the boundary you have a abrupt increase of charge to the positive side which relate to the fact that you have an n-type material on your left hand side from which the electrons have left and some holes have moved.

So, given this combination you have the charge being positive here it is negative here, and then again once you cross this boundary here, which is a relatively sharp boundary it again becomes charge neutral. So, this is again charge neutral value okay. So, this is how the charge density varies as you go from left side of the sample to the right side, which you go from the p sample to the n sample n side of the sample. So, now, from this we will try to understand how the field looks and how the potential looks for this sample.

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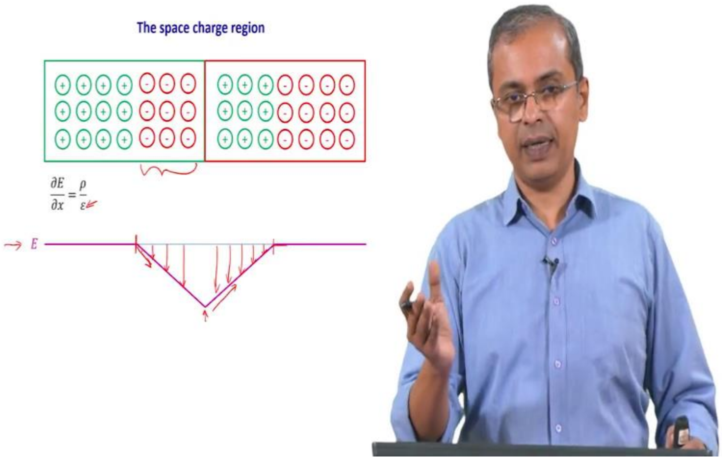

The space charge region

$$\frac{\partial E}{\partial x} = \frac{\rho}{\varepsilon}$$

So, if you look at the field the equation that defines the field is simply that the you know dou E by dou x is simply this charge density that you have their divided by the permittivity right. So, this is dou E by dou x is rho by E is what we have. So, we saw in the previous case that you had a negative charge in this region. So, it simply means the slope of the field is going to be negative.

So, it starts off again with a neutral field, because there is a you know neutral material when you arrive at the boundary, because the charge density is negative and it’s a constant negative value, the slope is a constant negative value and then therefore, the slope goes downwards. Okay so, that’s how the slope goes downwards and so, you see this coming down.

As you cross the boundary here the charge suddenly becomes positive and therefore, the slope here this rho by E goes from being a negative value to a positive value rho by epsilon goes from negative value to a positive value. So, from this position onwards the slope is positive and it again goes to this boundary here, where it again becomes a flat value and that is how the field varies as you go from left to right. So, you saw how the charge varies as you go from left to right and we have also seen how the field varies as you go from left to right.

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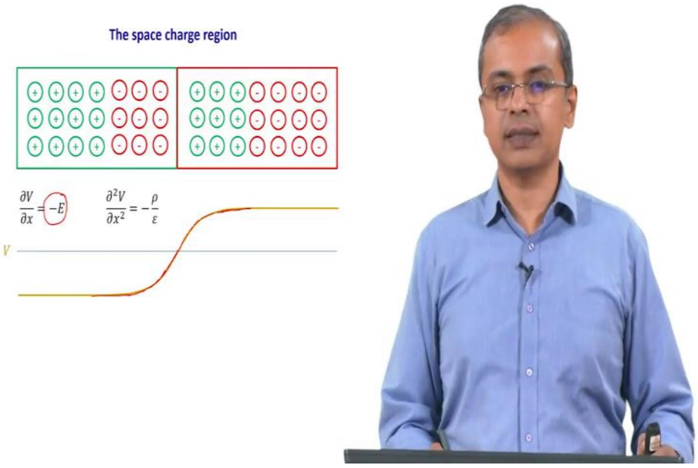

The space charge region

$\frac{\partial V}{\partial x} = -E \qquad \frac{\partial^2 V}{\partial x^2} = -\frac{\rho}{\varepsilon}$

If you go to the potential of this sample as a function of position, then it relates to the slope of the potential or the partial derivative of potential with respect to position is this minus E okay. So, we saw previously here that the E is actually starting off at the boundary value at this boundary and then going to steadily more and more negative values right.

So, therefore, minus E is going steadily to more positive values and it is going to higher and higher values. So, it is initially it is minus it is E which is this much and then it E becomes this much E becomes. So, it is becoming more and more negative here. So, therefore, minus E is becoming more and more positive, which means the slope of this potential curve is steadily increasing. So, not only is the slope positive it is also steadily increasing, which is what you see here it is a flat region up to here and then it starts becoming a positive slope which is continuously increasing.

So, it is continuously increasing right. So, that is how the slope is increasing; if you go back here now the slope reaches one maximum negative value, and then starts decreasing in value in negative value this way till it reaches 0 okay. So, it decreases steadily a negative negative values and heads toward 0 therefore, the slope effectively which is a minus E starts off at a high positive value and now decreases in slope. So, that is why the slope is continuously decreasing here and then it decreases off to a flat value and then that’s what you see here.

So, that is how you get this curve for the potential as you go from the left side of your sample to the right side of your sample.

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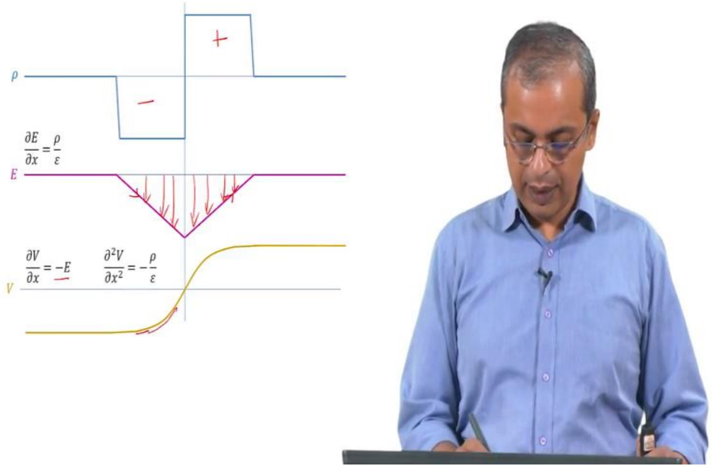

$$\frac{\partial E}{\partial x} = \frac{\rho}{\varepsilon}$$

$$\frac{\partial V}{\partial x} = -E \qquad \frac{\partial^2 V}{\partial x^2} = -\frac{\rho}{\varepsilon}$$

So, if I put all 3 of them together this is what it is, you can see here the negative charge the positive charge and because the negative charge gives you the slope of the E versus a supposition curve, it’s a constant negative slope here and then a constant positive slope here, and then the value is continuously increasing and then continuously decreasing. So, if you take that with a negative sign you have a value that is going to more and more positive values which is what you see here increasing positive value, and then a slope that again decreases in positive value till it levels off. So, this is the curve. So, I will close this description with just a couple of more points here on what would happen when you took this material and used it in a p-n junction.

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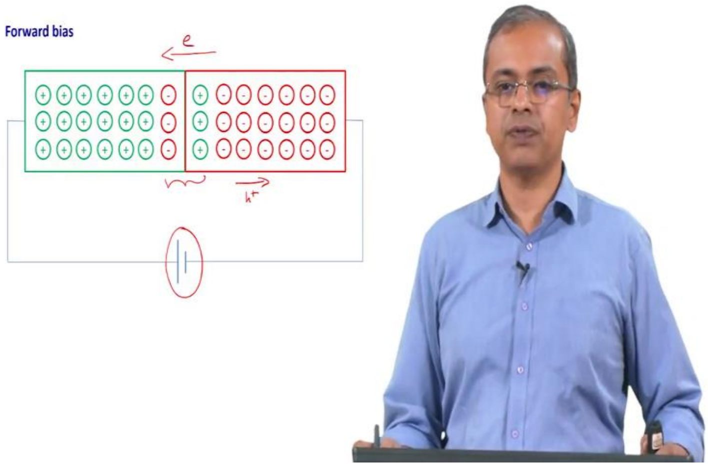

So, as I said you know this you can connect this to a some source of energy, and if you can connect the negative to the n side and the positive to the p side, this would be considered forward bias. So, basically what we are doing is, we are pushing more electrons in here and we are pulling them away from this side. So, that is essentially what we are doing.

So, when that happens, you are in a position to push more electrons into the boundary into this charged space charge region or the depletion zone and similarly as you draw electrons away you are sort of pushing more holes into this region. So, therefore, in the forward bias this is basically what happens your depletion region decreases in size and if you increase the potential from coming from your battery steadily. So, some value you have used previously you make it more and more a higher value, essentially the charge the space charge region will disappear, and you will have a steady flow of electrons e minus that way, you will have a steady flow of holes this way and so, this direction of the flow of holes would be the positive current and. So, that is how the p-n junction will work in the forward bias.

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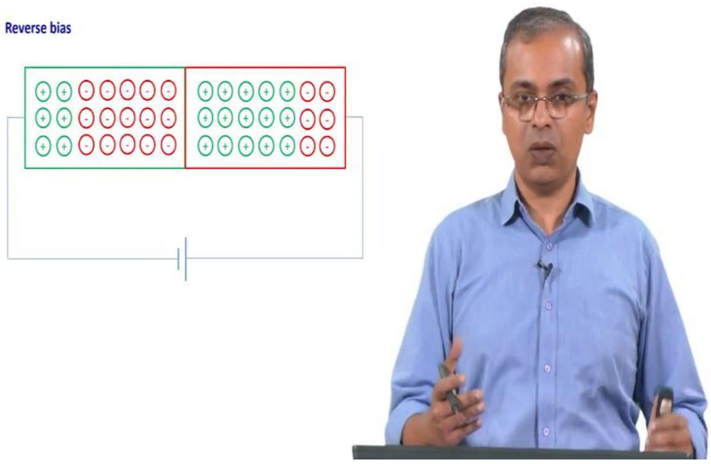

Reverse bias

If you use the same thing in the reverse bias, you can actually again you know put the positive and the negative the positive will now be in contact with this n side and the negative is in contact with the p side and so, what your draw doing is you are pushing electrons in here, and you are trying to draw it away from here.

So, then if essentially what you are doing is, you are increasing the positive window here and you are increasing the negative window here. So, you are increasing the depletion region or the space charge region. So, in from starting from here it will look something like this. So, you are increasing this region and this greatly resists the flow of current because it is now we know in opposition to the the potential that you are trying to force through the system.

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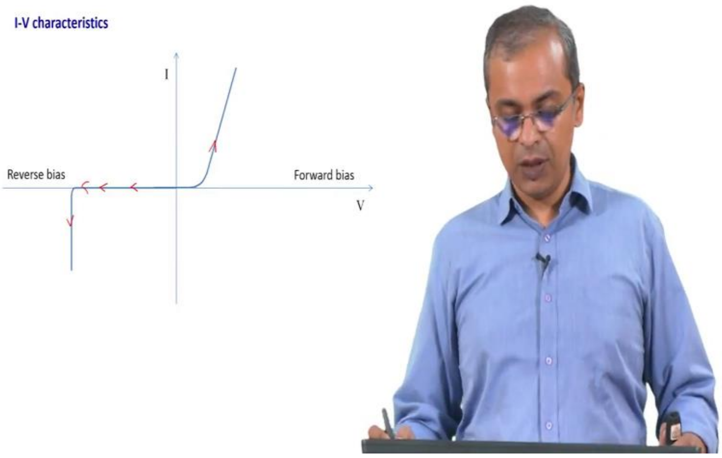

I-V characteristics

And therefore, if you look at the current characteristics it will look like this in the forward bias, because the depletion zone is continuously decreasing. Very quickly you reach a point where the depletion zone disappears and you have a steady flow of current. In the reverse bias when you go, you are actually increasing the depletion zone. So, you keep on increasing it till you reach the extent of the sample, and then you are actually breaking through the sample and going down. So, it’s kind of a break down voltage and that is how you end up seeing this.

So, you have a very you know asymmetric I versus V characteristic for a p-n junction based on whether it is biased for you know forward direction or in the reverse direction, as necessary in our discussion with solar cell we will revisit this concept, but it is sufficient that you are aware that this is the case.

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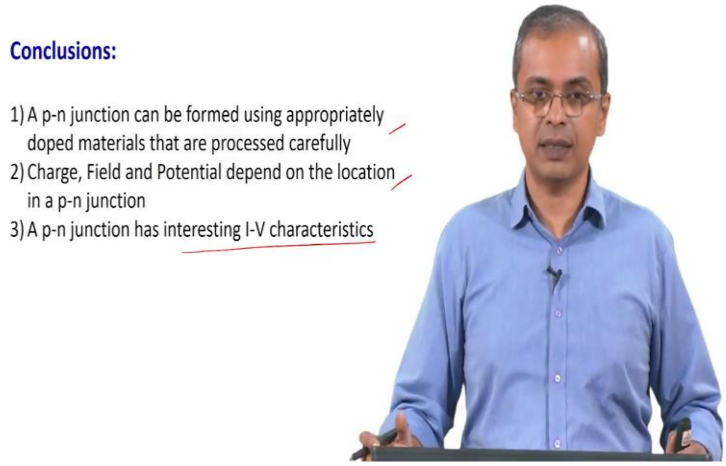

Conclusions:

1) A p-n junction can be formed using appropriately doped materials that are processed carefully
2) Charge, Field and Potential depend on the location in a p-n junction
3) A p-n junction has interesting I-V characteristics

So, I will sum up with these conclusions a p-n junction can be formed using appropriately doped materials that are carefully processed. So, that a particularly as I said the grain boundary is important it needs to be well defined, and you should not have any you know break in that boundary. The charge field and potential depend on the location in a p-n junction we had very interesting you know features on with respect to the charge density with respect to how the field was, and with respect to how the potential was.

And the p-n junction has very interesting I-V characteristics based on whether it is biased in the forward direction or in the reverse direction. And these are all concepts that we utilize as we use p-n junctions for a variety of applications including in the use of in the formation and use of solar cells. So, with this I will conclude for today we will pick it up in our subsequent classes.

Thank you.

KEYWORDS:

p-n Junction; Intrinsic Semiconductor; Intrinsic Semiconductor Materials; Silicon; Germanium; Intrinsic Semiconductor elemental; Intrinsic Semiconductor Compound; 3 5 Compound; 2 6 Compound; Group 4 A elements; Dopant; Extrinsic Semiconductor; p-type Extrinsic Semiconductor; Group 3 A elements; Group 5 A elements; n – type

extrinsic semiconductors; Boron; Phosphorous; electron; Hole; Junction Orientation; Depletion Region; Space Charge Region; Forward Bias; Reverse Bias

LECTURE:

Interaction of a p material with a n material and their interaction at the junction, the usage of periodic elements as dopants were discussed for Solar energy harnessing or photovoltaic application.