Electronics

Prof. D. C. Dube
Department of Physics
Indian Institute of Technology, Delhi

Module No. # 01
p-n Diode
Lecture No. # 01
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I am D. C. Dube. I have been here in the physics department IIT Delhi for nearly thirty five years. I shall be taking a course on basic electronics. It contains seven units, and these units are p-n diode, transistor, small signal BJT amplifiers, feedback and frequency response in amplifiers, field effect transistors, power amplifiers, and differential and operational amplifiers. This I am supposed to cover in 40 lectures.

So, today we start the first lecture which is the title is the p-n diode, and this will contain a brief introduction about the semiconductors in general, and then the first thing will be how the p-n junction is formed. And once the p-n junction is formed, what are the properties associated with the junction, how we can calculate some of these parameters like contact potential depletion width etcetera. So, this I shall be covering.

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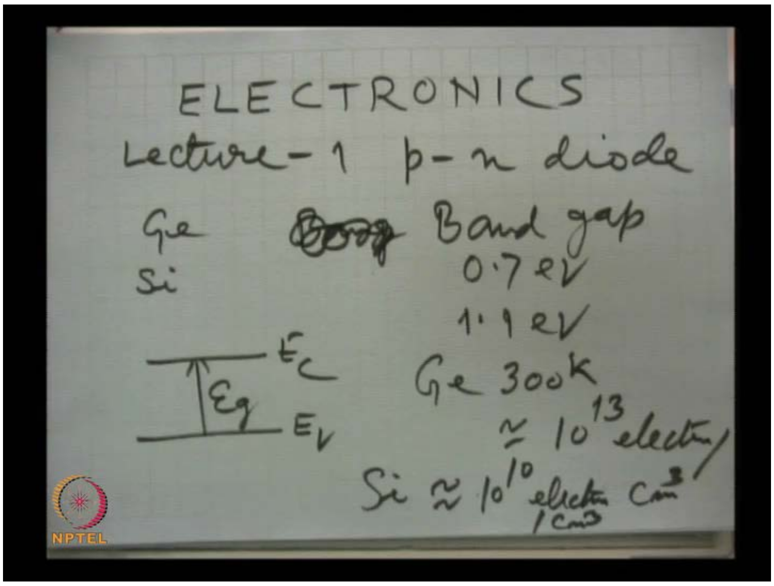

Let us a start with some few basics of semiconductors. As we all are familiar that there are two semiconductors basically the elemental semiconductors. One is germanium, and the other is silicon. Germanium has a band gap of Germanium has a band gap of 0.7 electron volt, and silicon has band gap of 1.1 electron volt. Of course, there are other semiconductors, compound semiconductors, gallium arsenide is also there, but for you it is sufficient if I talk about germanium and silicon. The first thing is that which of these two materials is better from device point of view. You see that germanium has a lower band gap, and this band gap is between the conduction band and the valance band, this is band gap.

Now in germanium the band gap is small so there are two things, one is that because of smaller band gap in a pure material germanium and silicon, the germanium will have a higher electron concentration that means the density of electrons in the conduction band in the germanium will be higher than silicon. For and this is actually the carrier concentration in germanium at room temperature 300 degrees Kelvin is around 10 to power 13 electrons per cubic centimeter. While in silicon because it has a band gap of 1.1 electron volt, this concentration in silicon is around 10 to power 10 electrons per cubic centimeter.

Now I often ask the students that, which of the two semiconductors they feel better which is better, and many times they tell me that germanium is better because there are 10 to power 13 electrons per cubic centimeter, which is 3 orders of magnitude higher than in silicon. But I want to point out one thing that when we make device out of these materials the semiconductors then there is no positive role to these electrons and holds of course, there is no role. The electrons in holes which take part in the process of the in the working of device, those electrons in holes are obtained by doping the pure materials. That we will see that how we get a n p type semiconductors by doping the semiconductors and what are the other significant things associated with them now.

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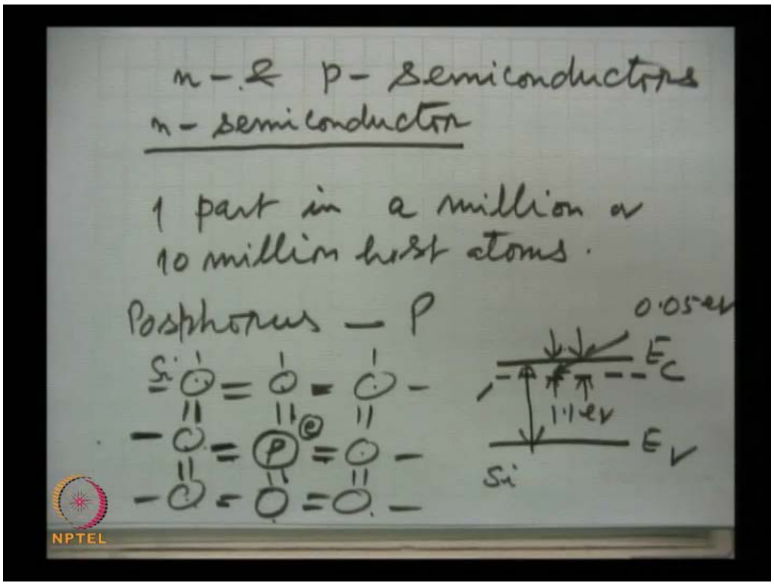

So, this is not the advantage for the germanium, that germanium has higher carrier concentration at room temperature or any other temperature. Another point is because of a smaller band gap in germanium, the germanium devices will be more temperature sensitive by temperature sensitive. I mean that the performance parameters will have a larger variation will exhibit larger variation with temperature, and which is again it is not desirable, because in our day to day life 40, 50 degrees variations are very common. So that on this two point we can say that silicon is a better material as compared to germanium.

Now what are how do we get n-p type semiconductors, n and p semiconductors are obtained by doping them. What is doping? Doping is a process in which we mix known very small quantities of a extended material. First I talk about n semiconductors. For n semiconductor we require a dopend the material which we are going to mix with it in a pure material. Remember that doping is very minute to the extent one part in a million or 10 million host atoms.

So, therefore by starting material should be should have the purity better than this, so these are very highly pure intensive materials. One thing also you should remember that in intrinsic materials when we talk of holes or electrons. These electrons are the once which are mobile when we apply the field these are not bound electrons. They have come to the conduction band after breaking a bound and leaving behind the energy state that vacant energy state is responsible for the creation of the hole.

Now let me take one example of the n dopent which is phosphorus. Phosphorus has a valancy 5 and silicon or germanium for that reason they have the valancy of 4. Now in doping is in such a small magnitude that it does not change the basic structure of host material, that means that the structure of silicon is not disturbed by the addition by the by this dopent. It dopent sits at certain lattice position in the crystal of silicon. I demonstrate you that how we can create this n type material

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These are silicon atoms, and the 4 electrons of each silicon atom that makes that form a covalent with the other electron from the neighbor. For example, this silicon atom these are the 4 electron of this silicon atom and they form covalent bonding from here and here the silicon atoms are there so they form the covalent bonds. Now phosphorus being pentavalent it has 5 electrons in the outer shell, out these 5 electrons the 4 will form the covalent with the neighboring silicon atoms, one electron is here other here one here and one here, the fifth electron it is extra there is low energy state available to it. And it is very loosely bound to the parental atom. How loosely bound? Actually we can calculate as we have done it as in the case of the binding energy of the electron in hydrogen. And because there the electron moves in the vacuum here it will move in the material.

So, the dilated constant the permittivity of the material will enter and this permittivity for silicon the real part of dilated constant for silicon is around 11.5. And so this electron force to its parent atom phosphorous is reduced further by this amount by the amount of the real part the permittivity of the material. And it works out that this is the conduction band edge, this is valance band there are no energy states for the pure crystal here, but when we dope it the energy states are created here, these are the energy states of the donor. We call it the fifth 5 grouping purities as donors because they donate one electron to each atom of the dopent will give one electron in the conduction band.

So, the energy states are here and this difference of energy while this is the band gap which is of the order of if we are talking of silicon this is 1.1 electron volt and this is a small fraction this is around this difference between these 2 is around 0.05 electron volt. This is very small energy. At room temperature the electron this fifth electron will have enough energy to move to the conduction band. This way each phosphorus atom will release it is one extra electron the fifth electron to the conduction band.

So, at room temperature k t k t the thermal energy is enough, and all the dopents can be taken as ionized. You know when we mix these dopents they are neutral but once it gives away it is one electron it is free to move within the material, it is not attached to the parental atom the phosphorus. So, this becomes a ion, deficient in one electron it becomes a ion positive ion. Now, there are few things which you should note one is, in intrinsic material when each electron which has moved to the conduction band it has left behind a hole here.

So, therefore in intrinsic material the concentration of electron and hole both are equal and in this case, this fifth electron has moved to the conduction band but it has not left behind a hole here. So, these electrons will be extra in axis of the electron or the charge carrier which were present in the intrinsic material. Now, another thing important which is very important that, in n semiconductor these dopent ions they have taken a lattice positions they take a lattice a positions. They are in mobile they remain in the system and they do not move, but still they play very significant role in that we are going to see soon.

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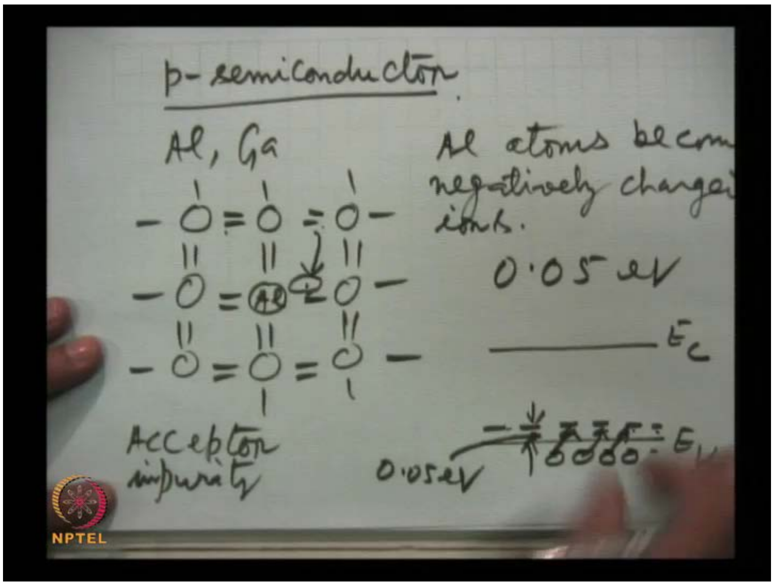

Similarly, we can talk of p semiconductor, here the dopent has to be a three group impurity like aluminum or gallium and so on. Normally, aluminum is used. Aluminum has valancy three, there are three electrons in the outer most shell of the aluminum and so what will happen when dope the material we dope silicon. For example, with aluminum here,

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This is aluminum and here the three electrons they will form covalent bond with the neighboring silicon atoms, and this position is vacant this is energy state which is vacant there is no charge carrier here. Now a electron from nearby silicon atom may jump into this and make into state and it will be trapped it will form a bond with aluminum. Now here the aluminum after accruing a extra electron becomes negatively charged negatively charged ion. And again it will take the very small energy of the order of 0.05 electron volt for these electrons nearby bound electrons to come to this energy state. And so these energy states are conduction band edge, valance band edge and here and this energy difference this is to the tune of as I said 0.05 electron volt or still smaller.

Now that means this much energy is required for this electron to jump, which is available as thermal energy at room temperature. And so electrons these bound electron they move to these states to make them negative ions and they create here holes. Again as I said in the case of the n type semiconductor that each electron which was released from the fifth group atom the dopent that was an axis in axis over the thermally generated charged carrier, otherwise that means as it happens in the intrinsic semiconductor. And here this electron when it moves to this impurity energy level here it has not left it has does not leave any electrons it does not release any electrons in the conduction band so this material will be rich in hole and this is called third group impurity, is called acceptor impurity.

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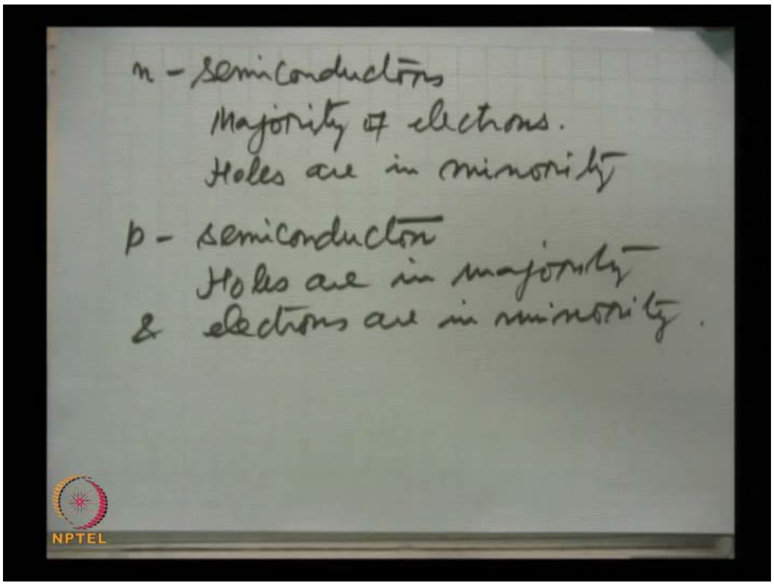

So, we will remember that n type materials n semiconductors they have majority of electrons majority of electrons and holes are in minority, in minority and p semiconductor holes are in majority and the electrons are in minority.

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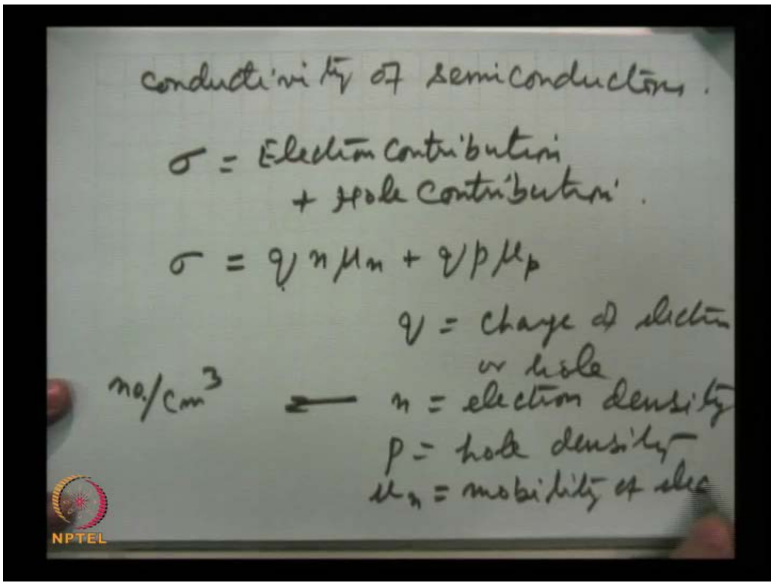

Now we can talk about the conductivity of semiconductors. Conductivity of semiconductor in general can be written as the electron contribution, plus hole contribution. electron contribution plus hole contribution Therefore, this is q the charge electronic charge and I write here charge of electron which is equal to the charge of holes time is different but we are concerned with the magnitude. So, charge of electron or hole and n is electron concentration, electron density, electron concentration or electron density one in the same thing and p is the hole density. These are they are expressed in number of electron for example, per cubic centimeters this is mu n this mobility of electron.

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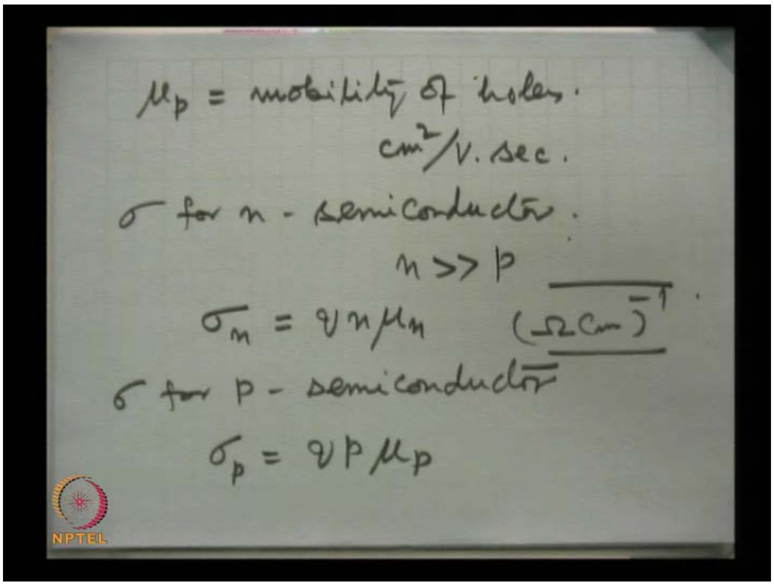

And similarly, mu p this is mobility of holes, and this is expressed in practical units are centimeter square per volt per second. Now this is the general expression for the conductivity. Now we can write from here we can write the expression for n semiconductor, conductivity of n semiconductor, conductivity of p semiconductor. The conductivity of, conductivity for n semiconductor, in this expression here the electron concentration will be much higher has compared to hole concentration. So, this term will be negligible will be several orders of magnitude is smaller than this term so the conductivity for n type material becomes q n mu n and similarly, conductivity for p type semiconductor this is q p mu p conductivity is expressed in practical units ohms centimeter inverse.

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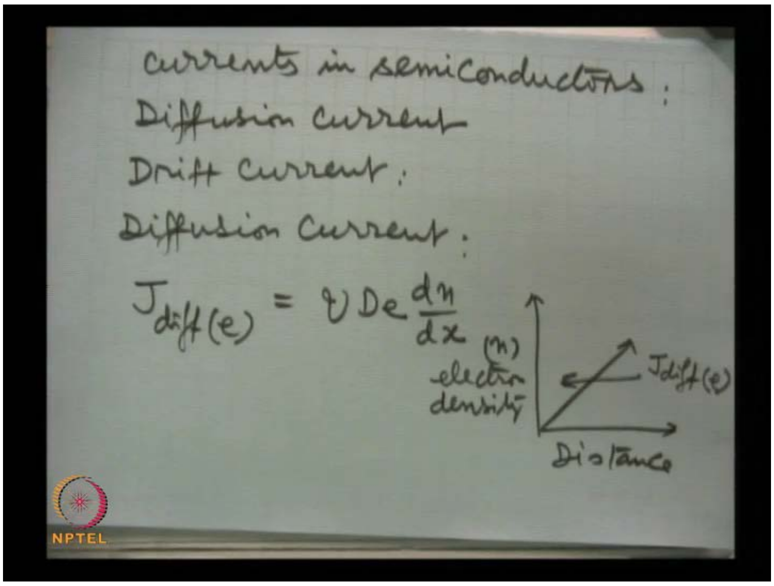

Now we talk about the currents in semiconductors. There are two components of current in semiconductors, these are diffusion current and drift current. First we talk about diffusion current, diffusion current arises as a result of carrier density variation if there is a gradient then electron. For example will try to diffuse from high concentration to the lower concentration regions. This is natural process like when there is a smoke in the environment then that is the smoke the concentration of carbon particles but then they gradually they diffuse to the region where the carrier concentration is much less. So, this arises because of the concentration gradient and this can be represented current density due to diffusion of electron this we recite as q D e dn by dx this is the gradient there is no variance this is current due to diffusion will be 0 this we can so like this is, this is distance, this is electron density now this is the gradient and the current conventionally.

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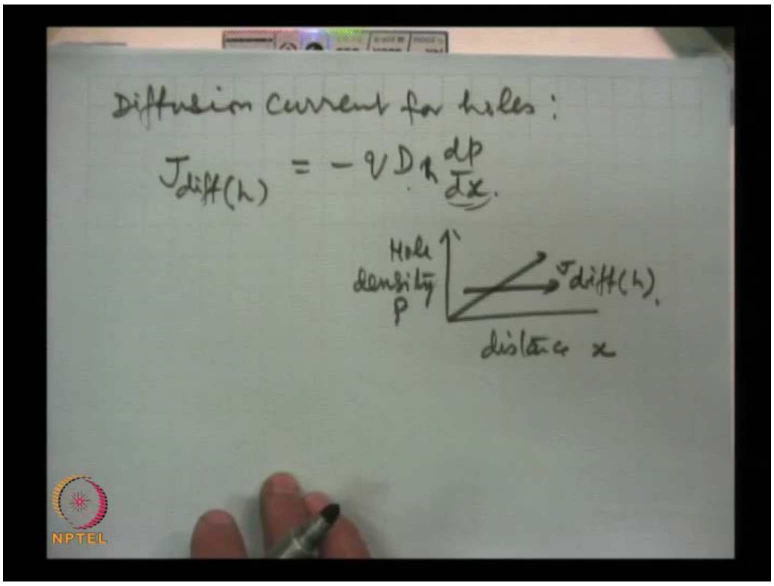

We take direction of current flow opposite to the electron flow, so this will be diffusion current this is J diffusion due to the electron. We can write similar expression for the holes so the diffusion current for the hole is this can be written as diffusion because of holes, this the diffusion constant for holes, this is the gradient the density variation with distance, this can be this is distance and this is hole density and this is the gradient and the current flows from higher density to lower. Current flows in the direction of holes and of course, hole movement because of opposite charge they move in the opposite direction to the movement of electrons.

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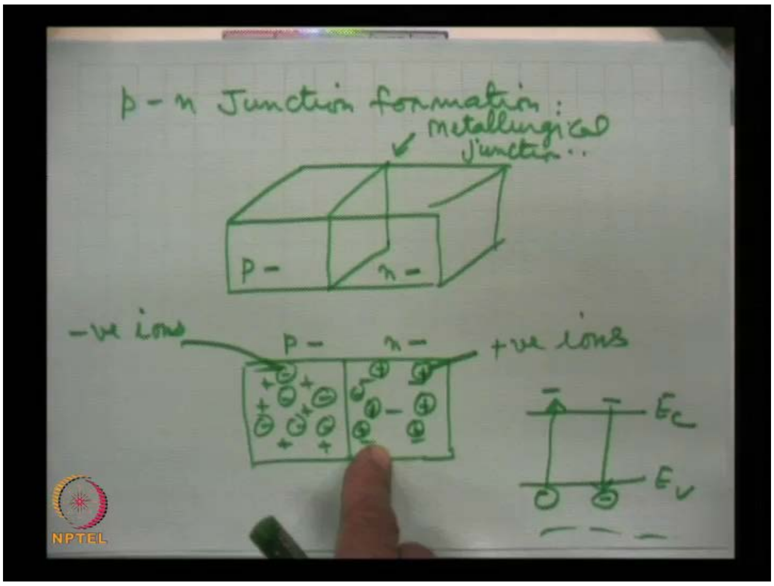

Now with this kind of religion we are in the position go for p-n junction formation. If we have a silicon crystal which is doped on one side with a p type impurity making p type and on other side n type impurity, making it n type. Then what will happen? So, let us draw a crystal, this is p region, this is n region, this is metallurgical junction this figure is in three dimensional, but normally it is sufficient to draw in two dimensions. So, this is t p region, this is n region, this is the metallurgical junction and these are the electrons, and with them there are negative ions. These ions play a role significant role, an important role so we cannot ignore them. Why they do not take part charge? Because they are not mobile they are rigidly fixed at the lattice and similarly here there are holes and there are positive ions this will be the positive ions.

Because in the donor has donated one electron, so these are the positive ions and here these are the acceptor atoms which had become negatively charged ions, because they acquire one extra electron, so this is negative ions. Obviously on the p side the density of holes is high, on the n side the density of electrons is high, for the time being we are ignoring electrons in the p region which are they are in the minority and here the holes are in minority we will talk about them later wherever that is required. Now this is very important, that if there is a structural continuity from the p side to the n side, then diffusion as a natural process will occur. So, holes will diffuse towards the n sides and electrons will diffuse to the p side, this diffusion will not occur if there is not structural continuity in the semiconductor.

That means, if we take a p type crystal separately, n type crystal separately and just we glew them together, then this diffusion will not occur. Because the barrier will be so higher physical barrier that that will stop totally the diffusion process p-n junction cannot be formed. So, remember p-n junction will be formed wherever n and p semiconductors are simultaneously present together and there is a structural continuity. Now how when diffusion occurs diffusion of holes from p side to the n side and diffusion of electrons from n side to p side this will start as a most natural process. And what will happen when holes diffuse from here and electron diffuse from here they both are free when they meet they recombine.

And you know recombination what happens? If this is conduction band gap, this is valance band gap. Recombination is the process opposite to the electron hole their generation, if this electron moves to the conduction band a hole and electron is generated this is generation process. Similarly, when holes are moving, electrons are moving they will recombine and a direct recombination if this electron jumps meets the hole it recombines. So, in the recombination electron disappears this hole there is no hole is no holds them because it just bound electron like many other electrons here and so on. Therefore, due to this diffusion a region will be created on both sides of this artificially region metallurgical junction and that region will be dividing of mobile charge carriers.

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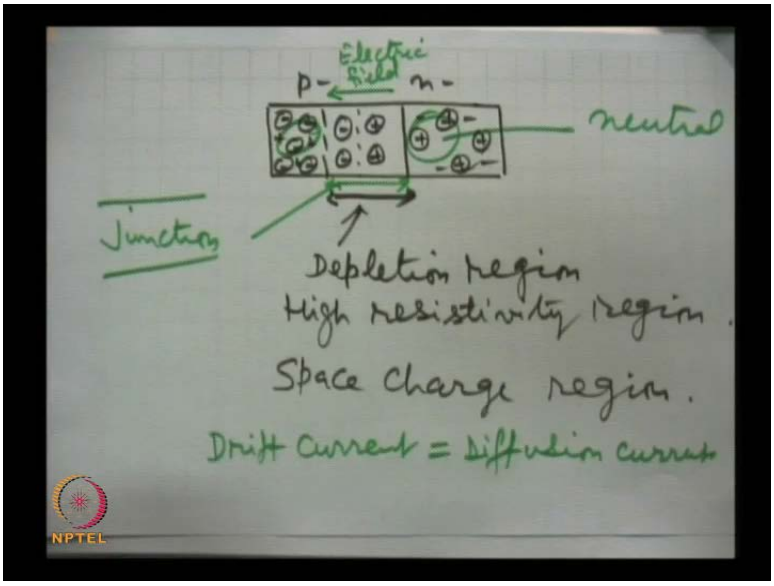

The situation can be illustrated like this

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From this region mobile charges have disappeared have depleted. Where they are gone? The holes and electrons met here and both recombine and I just now I explained that recombination the electron disappears. Disappears in the sense that it is not in the conduction band and the hole is also is not there, because they need to become a bound electron in the valance band like many other electrons. So, this region is dividing of mobile charge carriers it is a high resistivity region and this is called depletion region. It is a high resistivity region. Why high resistivity? Because resistivity of any material depends on the density of mobile charges, now here there are no mobile charges only static charges are there on the n side of this artificially drawn metallurgical junction, there is a net positive charge on the other side that means towards the left here this the n region.

So, this is a depletion region is space charge region here, this is neutral there are ions here too, and here the negative ions. But these positive ions are that their effect is virtualized in general because of the mobile electrons, here the effect of negative ions is neutralized by the presence of holes. So, overall if we look in any segment of the regions away from we call junction. This is neutral similarly, this is neutral, but this is not neutral here the that the charges which were neutralizing the effect of these charges they have been depleted. So this is depletion region, this is space charge region, it is a high resistivity region, actually this is junction, this is from here to here this is junction. And very pertinent question to how long this diffusion of electrons from right to left and holes from left to right it will continue there is another process which is coming out that diffusion will constitute the diffusion current.

But now these space charge will give arise to a field in this region with this polarity this is electric field and because of these electric field the holes here which were in minority. They will drift towards the p region and electrons which were in minority in p region they will drift towards the n region and that will constitute what we will call drift current. Now that junction comes in equilibrium when drift current is equal, drift current is equal to diffusion current here is a equilibrium which is established and the diffusion stops, drift stops. This thing for more clarity I draw another picture to summarize these current, this is hole drift current and electron drift.

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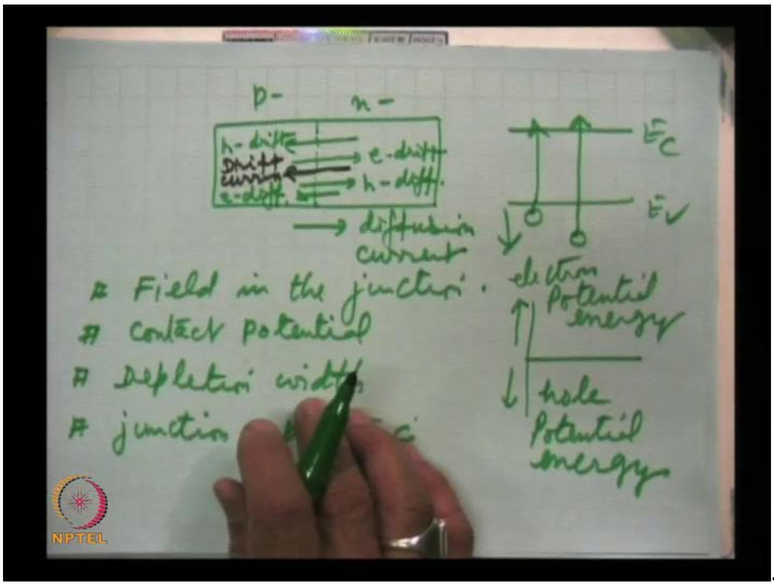

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So, there is a drift current in the direction of drifting holes. So, this is the drift current. Similarly, there will be hole diffusion and electron diffusion and that will give arise to diffusion current in this direction. The drift current was from right to left and diffusion current from left to right, they are in opposite direction. Equilibrium has been achieved has been obtained when the two currents as I said earlier drift current is equal to diffusion current. So, we will remember the properties of the junction that junction which is called depletion region we can find out the width of the depletion region. A space charge region is a that gives arise a space charge gives arise to electric field, what is the amount of electric field we can calculate that also, and it is a high resistivity region. So, all these parameters there is a field is always that gives arise to a potential that arise because of the potential, so what we call the contact potential.

Now contact potential the properties associated with the junction are the field in the junction, contact potential, depletion width and junction capacitance like that these are the properties associated with the junction. We will find an expression these for these quantities in the next lecture, we will also talk from another angle from potential energy point of view, how the what the diffusion and drift will do and how a barrier is created in equilibrium with that will prevent the flow of holes and electrons. This is the p-n junction in absence of any applied field there is no external field so far we have talked.

Now one more fundamental thing I will tell you which will require in the case of further explanation. That when we talk of electron energy and hole energy then we demonstrate that the electron energy increases in this direction, this is electron energy for example, electron potential energy. But, the hole potential energy is that goes in the opposite direction, this is hole potential energy and why it is just in a second I can demonstrate, that this electron goes here and if electron goes from here and this creates hole here so here this is higher energy than this meaning the hole energy goes in the opposite direction and we will continue.