Fundamentals of Semiconductor Devices

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Lecture – 14

Continuity equation (contd.) and introduction to p-n junction

Ok welcome back. So, we had concluded the last lecture with continuity equation and I told you how excess carriers decay right. And we derived the continuity equation and we told what the importance of this equation is, that is to find out the excess carrier density, because that will give you the sorry diffusion current and drift current of course, depends on field for that also you need the carrier concentration right.

So, it is very important to understand continuity equation that was the main essence of the last lecture. And I told you the today we shall start p-n junction and maybe before that we can give a couple of examples of how the continuity equation is useful right. And once you start p-n junction then many other devices you know will become very easier to understand like BJT’s or solar cell photodetectors, LEDs; they are all essentially p-n junctions. And eventually also we will touch base MOSFET because MOS transistor is the classic device that we have to learn in this course right.

And we will always take you know help examples take examples of realistic devices, real technologies that are going around. So, that we are able to calibrate ourselves as to what we are studying is in relation we is relation to what actually is around in technology. So, we shall begin from the continuity equation where we left in the last class; we will come to the whiteboard now.

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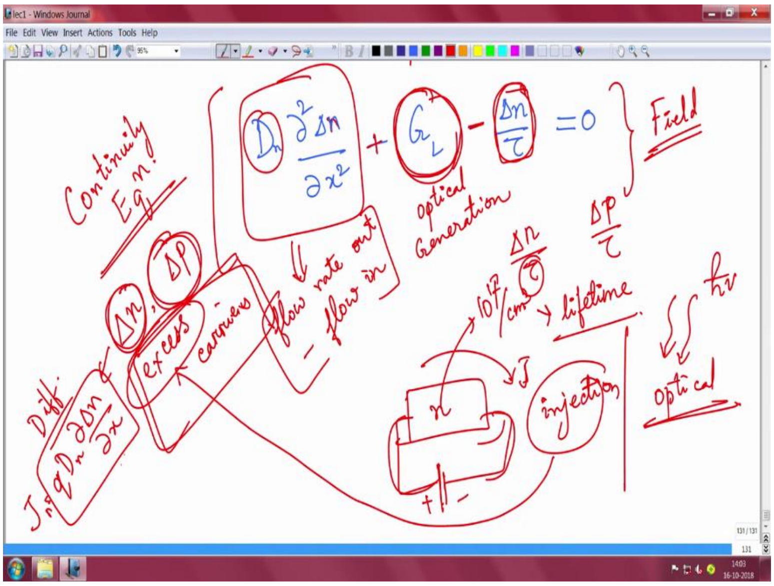

So, if you recall in the last class I had written down the continuity equation; if you recall the continuity equation it was D_n, the second derivative sorry the second derivative of excess carrier with respect to position plus the optical generation rate minus the excess recombination that will take place is equal to 0 i.e.

$$D_n \frac{d^2 \Delta n}{dx^2} + G_L - \frac{\Delta n}{\tau} = 0$$

Now, let us pause for a minute and try to understand again ok; this is your optical generation or any excess carrier generation that is happening; mostly by optical excitation. So, if you are shining light then you will generate some excess carrier that is what this rate means. This is basically meaning how the carriers are recombining and decaying. If you recall Shockley Hall Read (Refer Time: 02:17) statistics because of a traps or because of electron hole combination; you will always have excess carriers will recombine.

Electrons and holes will recombine and getting lost and that recombination is captured by this thing; you know always remember that recombination rate is Δn by τ of course, if there are holes then will be Δp by τ. And this τ is essentially the lifetime with which they are decaying; the excess carriers are decaying. And that is why it is a negative sign here because it is losing the carriers are recombining and loosing, there is a positive sign here because carriers are generating you know they are exciting and they are generating optically for example. And this term refers to essentially the particle flow rate in and out right; the flow rate that is out minus the flow rate that is in.

Essentially tells you the flow you know that in a particular in a particular sample; carriers are coming in and out going out because of current and that rate build up is basically captured by this. It is the second derivative of the excess carrier and there is a diffusion coefficient of course, here. We had neglected electric field in this equation I told you; if you put electric field it will become little bit more longer. We are not discussing this in the course right now, but if we necessary we will discuss that as and when the necessity arises.

Now, again let us take a pause minute to pause and ask ourselves this is continuity equation by the way ok. Now the question that we should again ask is what is the use of this continuity equation? Is there any benefit to actually understanding and deriving this mathematics of this equation? Yes, because the continuity equation; I hope you remember that derivation, the continuity equation essentially enables us to estimate Δn or Δp which is the excess carrier concentration ok.

And you will ask why is it excess carrier necessary? Excess carriers can be there in a semiconductor either when you apply a voltage. For example, you have an n type semiconductor, its equilibrium, but the moment you apply a voltage; the moment you apply a voltage, you are actually injecting carriers know, you are injecting because there will be current now that is flowing. And the moment current is flowing, there is an injection of carrier right; there is an injection of carrier from this is a battery. For example, it will inject carriers know; either electrons or holes right, that injection of carriers leads to excess carriers in the sample right.

So, in equilibrium for example, the sample had a concentration of $10^{17}/\text{cm}^3$, but once you apply voltage and current flows; then excess electrons and holes are injected right. So, that excess carrier comes because of either this or it can come because of optical shining ok; it can come because of optical shining or it can come because of many other reasons many other reasons.

So, whenever there is an excess carrier which is Δn and Δp; your continuity equation helps estimate that excess carrier concentration. And once we know the excess carrier concentration we know the current; for example, diffusion current depends on qD_n for example, Δn by Δx right.

So, that is why you know we need to know the excess carrier to estimate current density. Because only when we know current density, we shall be able to analyse the device performance ok; we shall be able to analyse the device performance; that is why continuity equation is so important in this context. Now when you solve continuity equation; there are different boundary conditions that we have to look into, depending on the situation.

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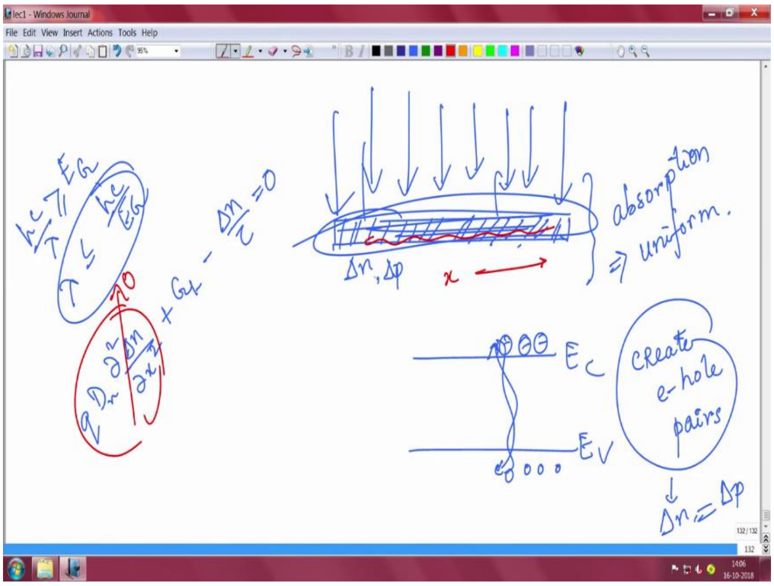

For example, if I take a very thin; let me not draw it here; suppose I take a very thin slab of semiconductor is very thin is very thin and its uniformly say you know n type doped for example, I am shining light of wavelength lambda that is absorbed here completely.

So, around everywhere the absorption is uniform I am shining everywhere. So, everywhere in the sample, the absorption of the light the absorption of the light is uniform ok; the absorption of the light is uniform. And so when you absorb light in a semiconductor, you what will happen is that you of course, know that excess carriers generated. So, electrons from the valence band will get energy because of the light to go to conduction band and keep this electrons leave behind holes.

So, essentially you create electron holes pairs; you create electron and hole pairs when you shine light that is absorbed ok. The light has to be absorbed of course; so here I assuming that light is absorbed. I told you once that for light to be absorbed, the energy of the photon hλ/c has to be greater than equal to the band gap. So, the λ has to be less than equal to your sorry this is I am sorry hc/λ. So, hc/λ has to be greater than equal to the band gap; so lambda has to be less than equal to hc/E_G.

So, only in that condition your light will absorbed. So, once your light is absorbed you create electron hole pairs; when you say electron hole pair, this actually means Δn and Δp. You are creating extra electrons and extra hole and always extra electron excess electron is always equal excess hole because for each electron that is going you get a hole here right. So, that has to be always equal.

So, when you absorb uniformly here; then you know there will be no diffusion because you know everywhere the carrier concentration; excess carrier concentration is Δn, Δp is same everywhere. And then you can solve the continuity equation there to find out how it decays it time for example. So, as long as it is shining what will happen? You recall the continuity equation the continuity equation is

$$D_n \frac{d^2 \Delta n}{dx^2} + G_L - \frac{\Delta n}{\tau} = 0$$

Now, see everywhere it is uniformly shining; so, the excess carrier concentration everywhere is the same. So, there is no gradient of the excess carrier; if there is no gradient of the excess carrier with respect to distance; this is distance right then this quantity becomes 0 because over any distance x it is the same.

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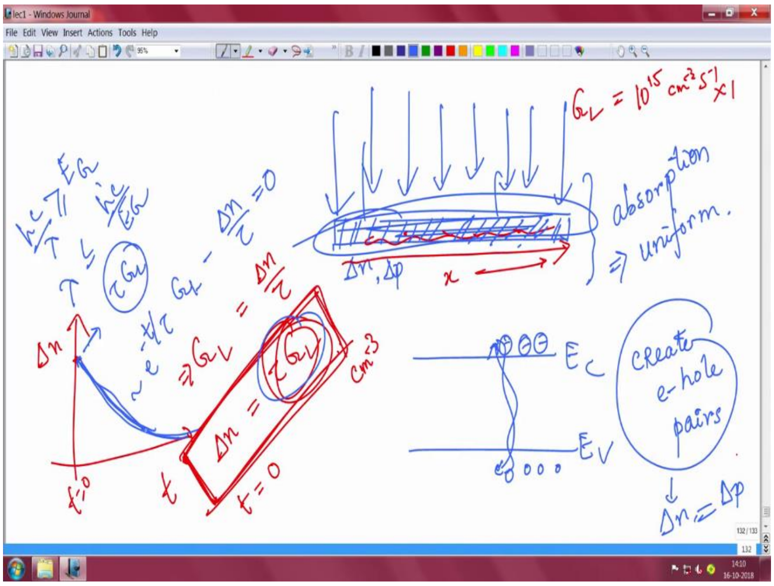

So, what happens is there then I can solve this equation and I will just say that you know from this I can say the optical generation rate is equal to Δn by τ. So, the excess carrier that is generating Δn or even Δp is equal to τ times G_L; so that is the excess carrier that is generating uniformly.

So, optical generation the light that your shining will have a given G_L; say it might be 10^{15} $cm^{-3}s^{-1}$. So, that you multiply with the lifetime; so the lifetime of say you know nanosecond whatever. So, you will know how many excess carriers we are generating essentially this is unit is per centimetre cube.

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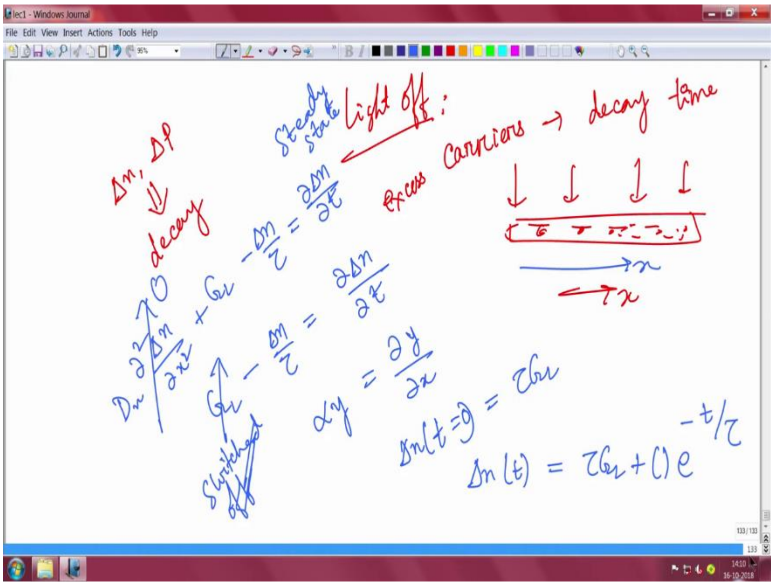

Now, the moment or light is switched off; the moment light is switched off; if you switch off the light for example, then the carriers will decay with time; not distance, everywhere it was uniform know. So, carriers the excess carriers will decay with time.

And by doing this measurement actually experimentally you can measurement, do the measurement of the carrier lifetime. So, once you switch off the light, what will happen? The excess carrier that was there in the sample they will decay, they will decay with respect to time not in position why? Because everywhere else the light was shining equally; so, everywhere the excess electron-hole (Refer Time: 09:27) generation density is the constant with respect to distance. So, there is no diffusion anything, but the time it will decay; so what will happen; what will happen now?

So, you have to solve the continuity equation again right with the boundary condition that with the boundary condition that; exactly when your light switch light is switched off; at that moment. At t = 0 suppose you have switched off the light at that moment this was the excess carrier because this was the uniform excess carrier density.

So, the moment you switch off the light; you get this was the excess carrier that was that was preserved that was that was persistent there. Now switch off the light, so this excess carrier will decay from this value which means, if I plot delta n at any point; any point I can take it is the same with respect to time. Then at time t = 0, when I switched off the light, this is the excess carrier that was there, this point is actually this; this point is actually this is τ times G_L this is the extra value here and it will decay from here like this exponentially; it will exactly like go asymptotically to low value here.

So, that will decay exponentially and how do you actually do that? You solve the continuity equation again with that boundary conditions. So, now you know the continuity equation is again

$$D_n \frac{d^2 \Delta n}{dx^2} + G_L - \frac{\Delta n}{\tau} = 0$$

Actually we put this as 0 because it was in steady state that is why we put that is in state. We put this is 0 because if you recall the derivation, this is actually not 0 we put it 0 because in steady state it is 0, but now it is not steady state when you switch off the light actually this was delta n by dt it was with respect to time.

This is again 0 because there is no change in the x you know everywhere it is same. So, essentially what happens is that you have

$$G_L - \frac{\Delta n}{\tau} = \frac{d\Delta n}{dt}$$

But this will be 0 now; why? Because you have switched off the light; you have switched off the lights or optical generation goes to 0. So, essentially it is like you know some constant times y is equal to dy/dx excuse me.

So, you can find out the solution in the appropriate boundary condition that Δn/τ is equal to 0, at equal to 0 at equal to 0 Δn; it was τ into G_L. So, if you solve that then you will find out Δn as a function of τ will be actually τG_L plus some constant and the exponentially it will decay -t/τ. So, as I told you it will decay exponentially like that $e^{-t/\tau}$.

So, if you switch off the light experimentally and you measure the carrier density; you will find an exponential decay if you take the exponential decay and you fit it. I am talking about experimental measurement; then you will be able to find out the carrier lifetime tau that is how people find out the carrier lifetime. So, this is an example of how you can apply the continuity equation; this was just a block of semiconductor without any bias; just you know very thin exposed to light completely.

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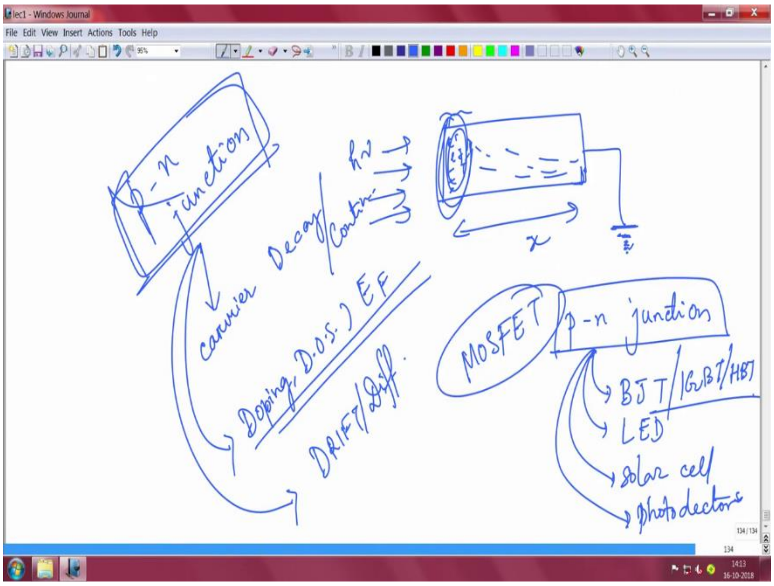

Similar exercises can also be done in some other cases. For example, if you have a semiconductor and this side is put to ground and your light is shining only at this side; your light is shining only at this side your light is shining at this side; so, electron hole pairs are generated here very large quantity.

But then in a few nanometre here electron hole pair will be absorbed and generated; light will not penetrate deeper because light will be absorbed. And then excess carrier here it will generate you know they will decay essentially; they will decay. So, for that also you can solve the continuity equation I will leave that an exercise.

You can solve the continuity equation you can find out how the carriers are decaying; this is with respect to distance this is sample distance so that you know in different circumstances you will be able to come up with a solution once you know the continuity equation; once you know the boundary condition; so, armed all these fundamentals and basics, now we are able to go into the discussion of p-n junction ok.

And p-n junction will depend heavily on the concepts of carrier decay; I mean carrier recombination and decay is the same thing carrier decay or recombination whatever we have learnt till now. Continuity equation it will depend heavily right; it will also depend heavily on the basics of your doping of your density of states that you learned, of your Fermi function and other things that you had learned right. It will depend also on your current flow, your drift and diffusion current will be very important in this right.

So, p-n junction will now involve many of these things and also everything that we have learnt till now will be used. So, it is important that we pause here and we basically make sure that whatever we have learnt till now; we are in sync, we are not able to lose we are not losing focus ok. Whatever we have learnt till now we should be able to recall as and when it is necessary because now we are going to study p-n junction ok.

And p-n junction as I keep telling will be the building block of BJT, HBT they are transistors of LED of solar cell of photo detectors and many other applications. Actually many other types of transistors also various other types of transistors like IGBT, HBT; they all will depend on p-n junction. Even MOSFET you will always need the basics of p-n junction anyways in MOS; in the MOS capacitance and all.

So, basically p-n junction is like the foundation on which many of the things are resting. So, we will have to really really carefully look at p-n junction.

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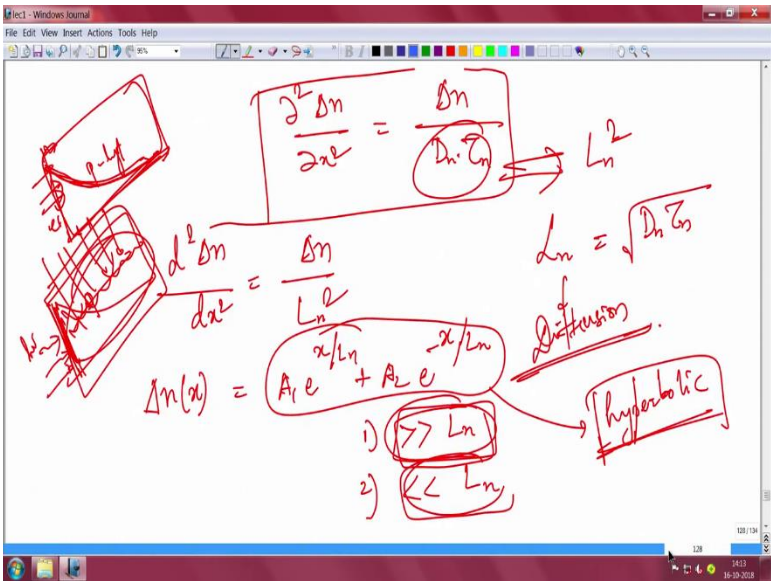

So, I am hoping that till this point in time whatever we have had studied things like you know excess carrier decay, continuity equation you know how we solve the continuity equation; how we derive the continuity equation; these are all clear to you.

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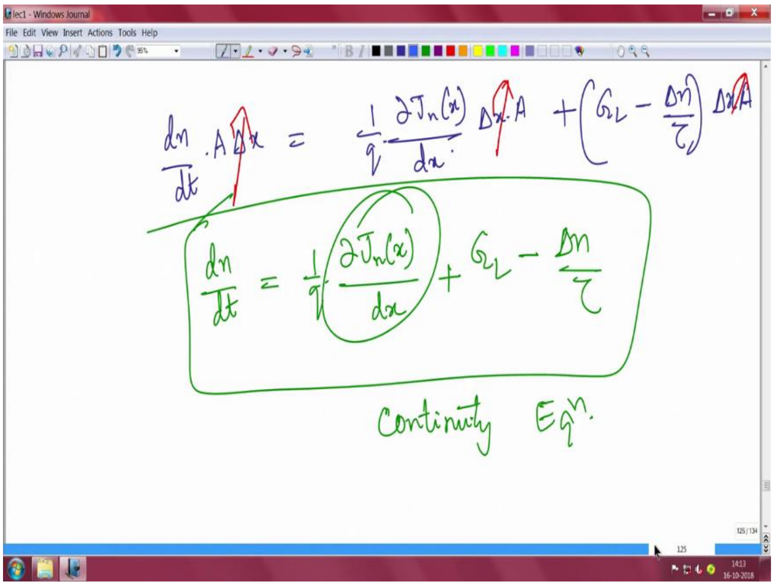

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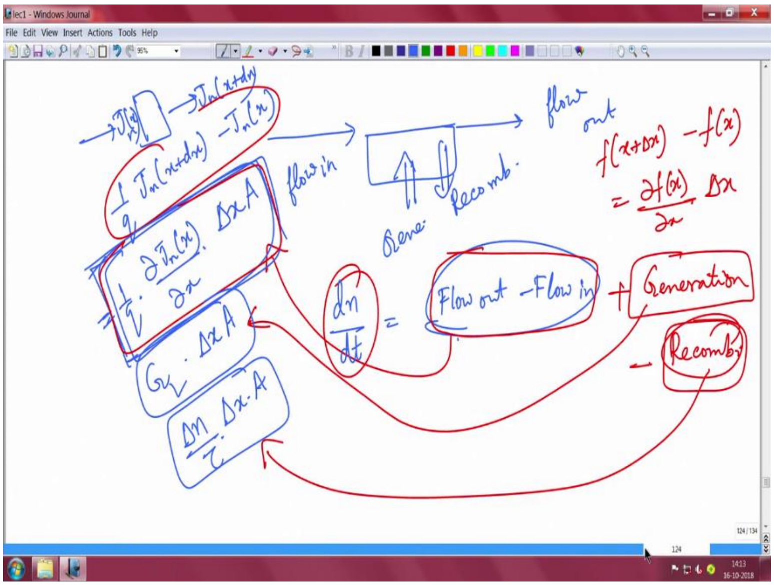

If you remember the low long diode the short diode things that I had discussed with you; the derivation of the continuity equation.

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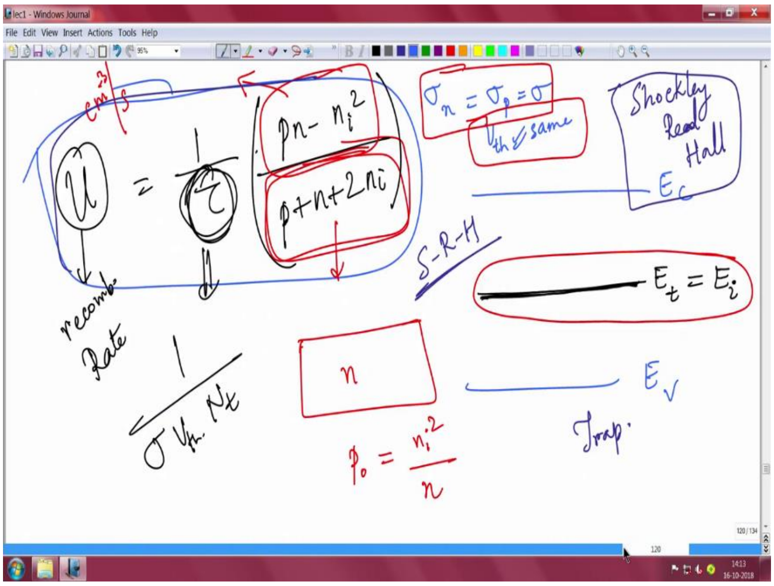

Shockley Read hall recombination was more about traps, how they recombine the carriers will recombine with the traps.

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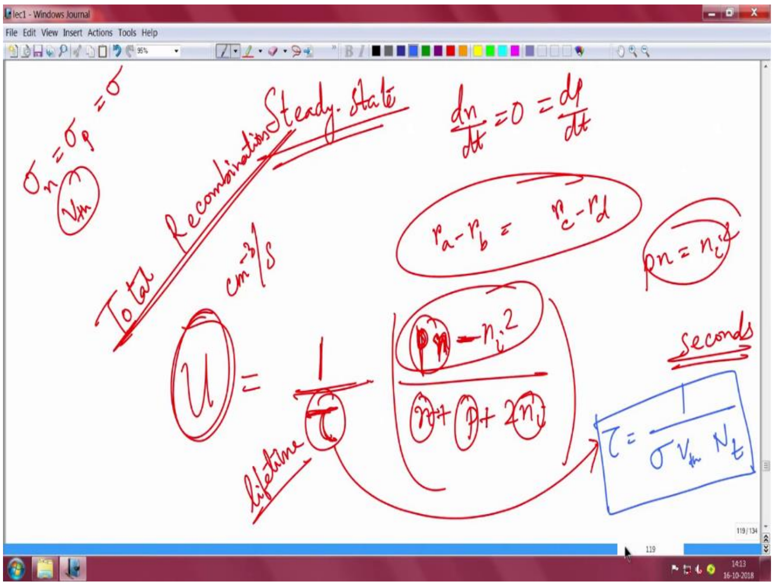

We hope you know you remember that those things and we had also done some simplified examples of that.

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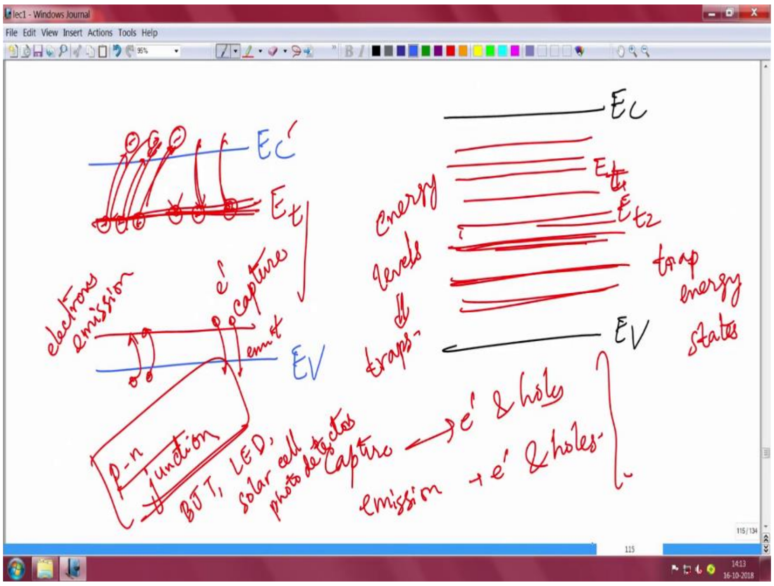

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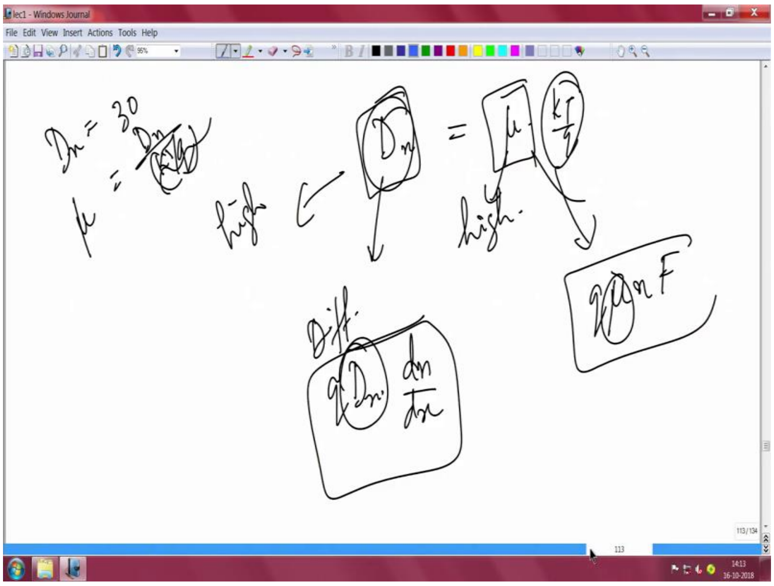

Trap dynamics and all we have studied that I am just recapping whatever we had learnt in the last few lectures.

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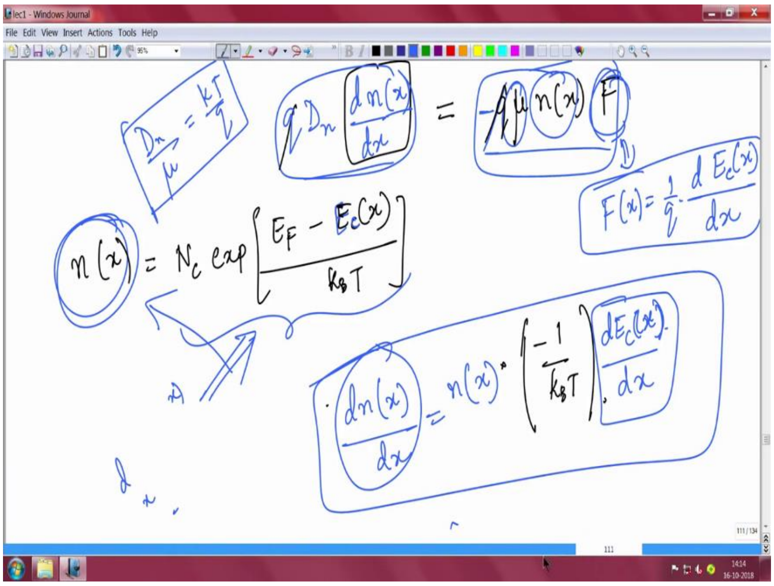

Einstein relation we had derived and this is very important Einstein relation essentially was the diffusion coefficient by the mobility is equal to kT/q. So, this will become very handy very useful in whatever we are going to do in the next you know discussion of the p-n junction so that we should not forget that.

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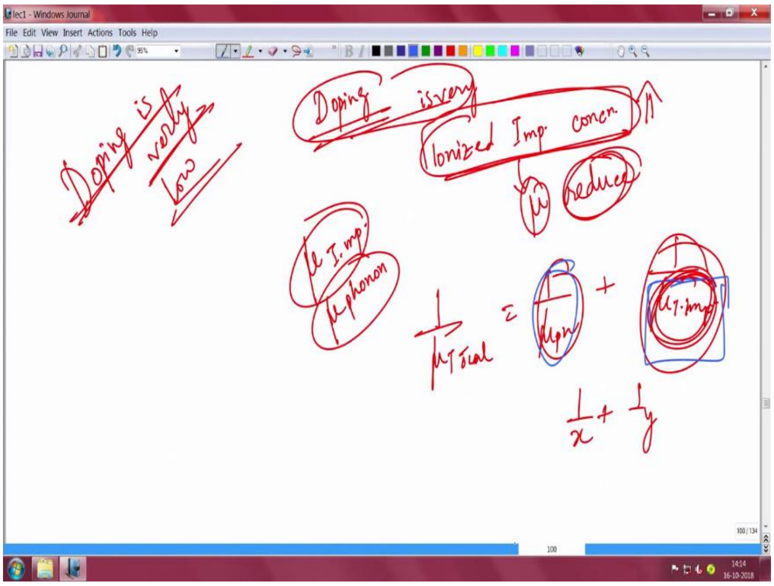

We had also discussed about drift diffusion basics; the derived expression for diffusion current, I also had derived expression for the drift current. Before that we had discussed mobility, how mobility is affected by carrier scattering from the impurities, from phonons which are nothing, but lattice vibration.

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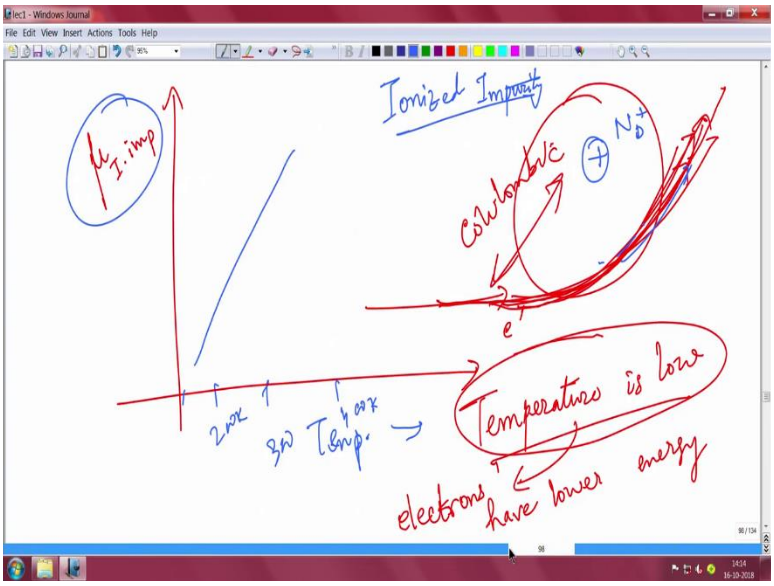

I also told you the definition of mobility what does mobility mean right.

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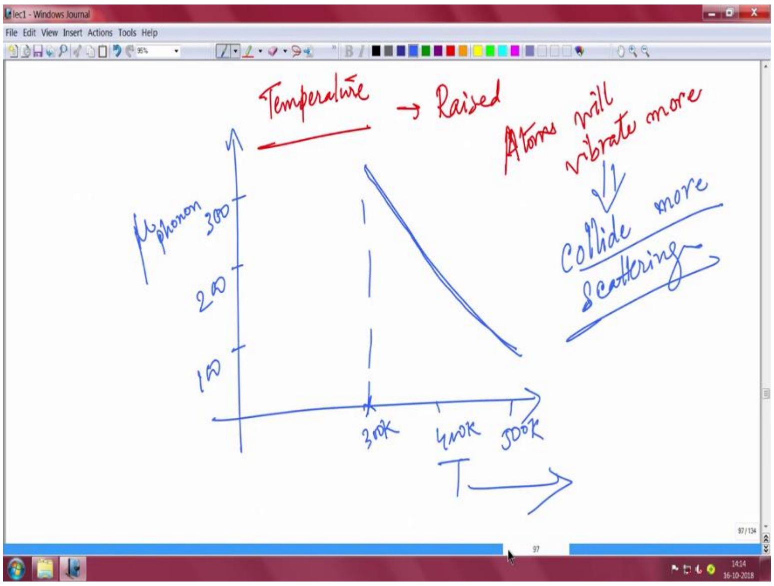

What is electron velocity, how electron velocity saturates, how mobility changes with temperature.

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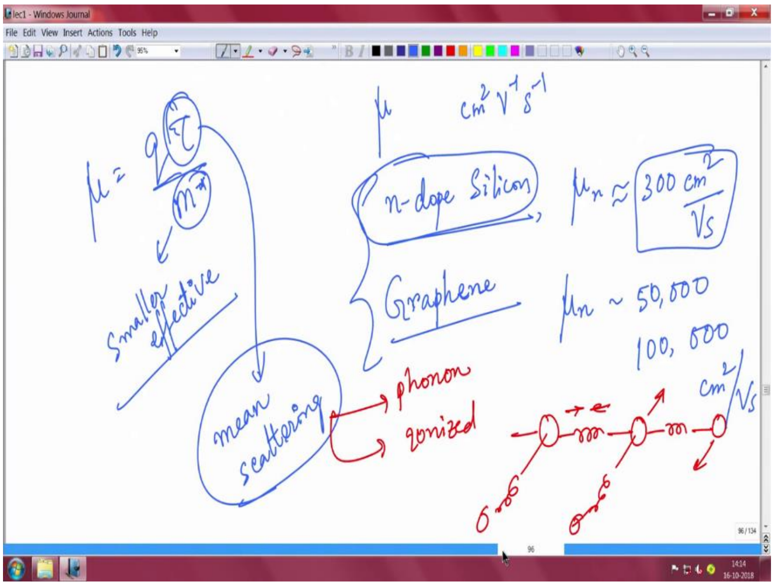

Electrons have their own mobility, holes of their own mobility, mobility of silicon you know electron in silicon for example, is 300, mobility in graphene or other material you know could be even 100, 1000 million at low temperature for example, and depends on the material, and I also told you that velocity does saturate you know all these things the carrier transport is decided, discussed. So, and at that is how we discussed in the last few lectures and of course, before carrier; carrier transport we had gone through other things like about your; your carrier statistics, density of states, doping, incomplete ionization, heavy doping effect, Joyce Dixon equation, partially incomplete ionization, heavy doping effects like band tail at very high doping the band gap will become lower; so many things we are discussed actually.

So, now we are armed with all of this and we believe that now you are capable of finding out you know about the details of p-n junction.

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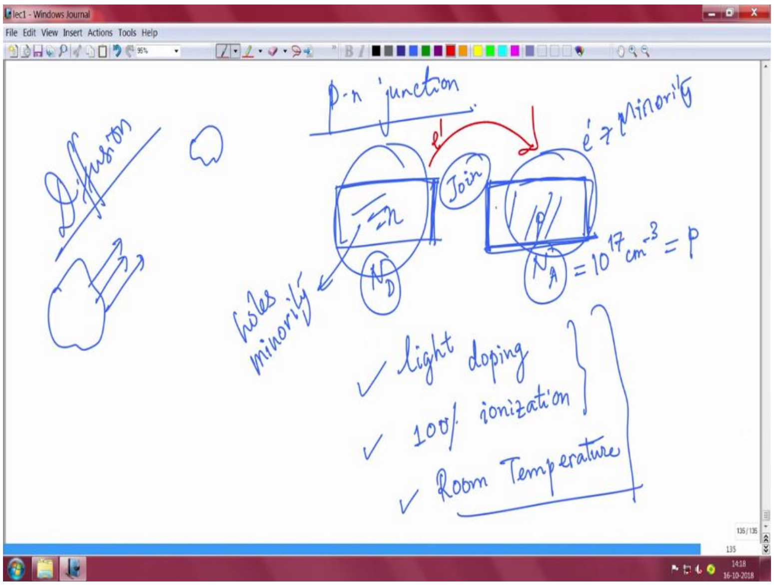

So, here we will begin the p-n junction fundamentals ok. We will begin the p-n junction and we will continue the next few lectures will be on p-n junction. So, there is nothing to be worried; so we will go slowly we will make sure that everything becomes clear here.

So, essentially p-n junction is very very very simple, you for example, take an n type material, you suppose you take an n type material electrons; it will be there will be majority of electrons here right. And then you take suppose a p type material right; you take a p type material, you are doping it acceptor density, some doping is there.

And consider these are; considered these are light or moderate doping. So, there is no heavy doping effects like Joyce Dixon and all; that is one approximation assumption we are taking. One assumption is that; there is 100 percent ionization of the dopants. So, there is no incomplete ionization or no partial ionization; which means if I am doping it 10^{17} of acceptor ions, then I am going to get exactly same number of holes.

There is no incomplete ionization that is an assumption, and the third assumption is that these are all at room temperature and equilibrium; so there is no light shining, you know no magnetic field, no electric field nothing. So, these are the conditions that we are going to assume.

So, I am taking n type semiconductor ok; I am taking an n type semiconductor; I am taking a p type semiconductor here. And the p-n junction is essentially formed when I join them, when I join them ok; when I joined them. So, what will happen when I join them? Now how do I join them physically? That is a different question, I do not put any glue or fevicol or something to joined them, that is not how it is done.

We will come that the fabrication later; when it is necessary, but suppose we are joining them, what is the thing that will happen when we join them? So, this side has is p type doping; so there are many holes. So, there are very few electrons on this side this side which are called electrons are minority. So, electrons are very low in concentration that you know and similarly on this side, the other side, because it is n type doped, holes are a minority; that means, hole concentration is very very low.

Now you recall what is diffusion? Diffusion is whenever there is a higher concentration of something on one side and a lower concentration of something on another side; the species will try to move or diffuse from the region of higher concentration to a region of lower concentration. So, there more electrons on this side, there are very free electrons on this side which means electrons will try to move from here to there right. Because you know unless you join they you will not move because there is a gap of air here, but once you join they will try to move.

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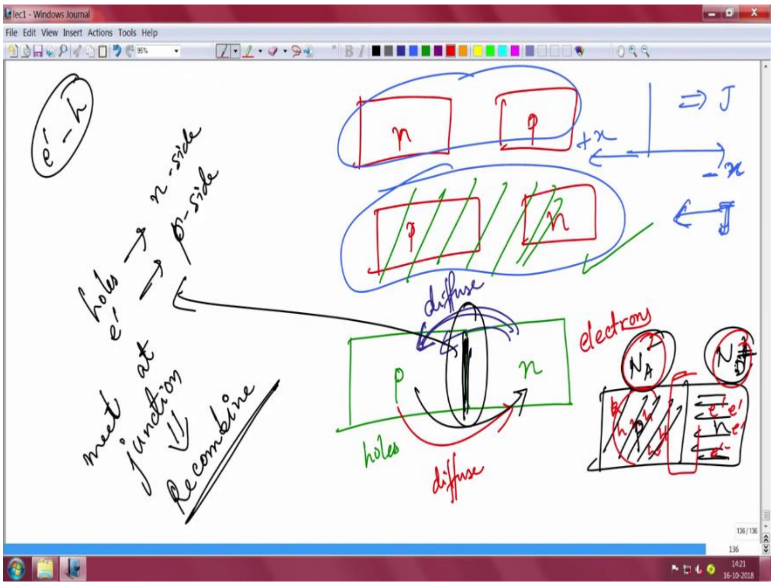

So, let us go to a new page and let us draw it again fresh. For various reasons, it is the same if you either take you take an n and p; n is on left side p is on the right side is the same as you taking p on the left side and n on the right side.

But it so happens and everything remains same of course, I mean if I joint this it is the same as this whether it is left or right does not matter, but conventionally we define this as the positive x direction. So, it will be good if the current is flowing in the positive direction; then you know the analysis becomes in general easier. I mean if the current is flowing in the negative direction everything there is nothing change; you know it is just an orientation different.

But then everything is we have put a negative sign because it is a negative x direction or we have to define this as positive x and this as negative x; which becomes little you know strange. So, there is no physical difference at all, but to make things simpler, we will go with, will go with this particular configuration. Because then electrons actually you know the current will basically be flowing to right you know that that make sense I mean better.

So, I will take a p type material and I will join with an n type material here. I will take a p type material, I will join it in n type material. I told you there are excess holes here; there are very few holes here. So, holes will try to diffuse from p side to n side because there are very few holes on the n side. And electrons are majority on the n side, but there are very few electrons on the p side. So, certainly electrons will try to diffuse to the p side; electrons are diffusing to the p side, the holes are diffusing to the n side, they will meet at the junction. Because and why are they diffusing? Because you know there are very few holes on the n side very few electrons on the p side they will diffuse because that has a concentration gradient.

When they diffuse you know of holes are diffusing to the n side and electrons are diffusing to the p side. While they are diffusing physically; they will actually meet at the junction, they will meet at this junction, at junction and the moment electrons and holes meet at the junction, they will recombine. And when they recombine, basically electrons and holes have recombined and they are gone right; they have recombined they have vanished now.

What leaves behind when an electron and a hole will recombine? See this entire p type region ,let me try again, this entire p type region is actually filled with N_A^- ok; that is ionized negatively charged ionized acceptor I told you. When an acceptor atom accepts an electron, because it gives away hole right; it gives away hole it that; that means, it accepts an electron it becomes negatively charged.

So, the ionized acceptors are negatively charged when they have given their holes, similarly on the n side ionized donors are positively charged because they have donated the electron now they are left with the positive core. So, the whole thing is filled up with positively charged core, whole thing is filled up with negatively charged core. But because their mobile electrons mobile holes here, which are positively charged and there are mobile electrons here which are negatively charged. So, they exactly balance this exactly balance that that why total charge is 0.

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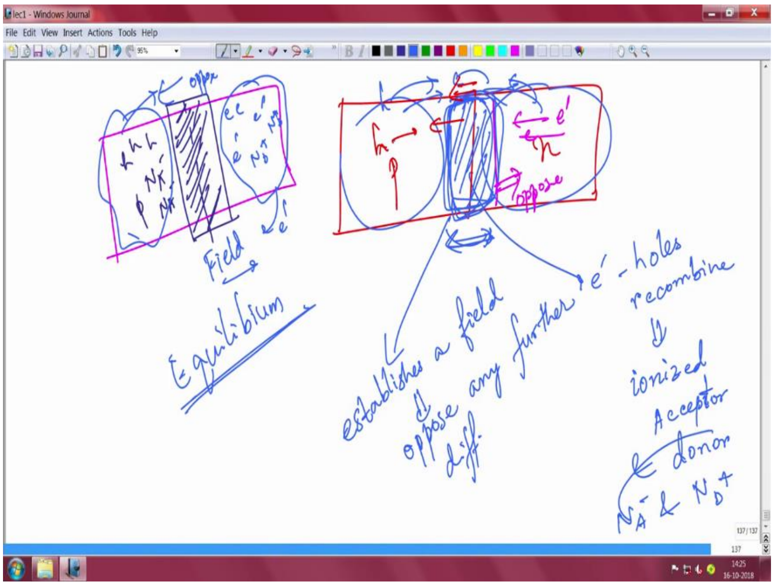

Now, at the junction, let me go to different page. I told you that holes are trying to go the other side, electrons are trying to come to the other side, and at the junction when they cross, they will recombine here.

And the moment electrons and holes are recombining, why they are recombining? Because they are moving to the other side you know; as soon as they recombine as soon as they recombine, they are gone, what is left behind in this region is ionized acceptor and ionized donor, ionized acceptors and ionized donors are left behind here. Because the mobile electrons and mobile holes have now vanished; they have not vanished from here, they have not vanished from here; they only a vanished near the junction, how near the junction we will come to that you know.

I mean what is the extent around this, is it like nanometre nano meter on both side, is it like hundreds of nanometre on both side; we will come to that. Now you might say that holes will still fine that is fine, that holes will still try to keep coming to the other side from here. Electrons will still try to come to the other side from here, but no that will not possible because as soon as they leave behind a positively charged and a negatively charged core here; this establishes a field, this establishes a field, electric field.

And that field will oppose any further diffusion of electrons or holes from the other side, that there will be a field that will develop as soon as they recombine and leave behind a positively and negatively charged ionized cores; that field will oppose, that field will oppose any movement of holes; the holes are trying to move here, this field will oppose that ok.

Similarly, electrons are trying to move this side diffusion, that field oppose that. So, that field will ensure that no further electrons and holes can now diffuse and it will reach equilibrium. So, essentially an equilibrium; what it will look like is that there is a junction here of course; some part around the junction like this, some part around the junction.

This is positively charged code negatively charged core that has been left behind because of the electrons and holes being mobile they are recombining. Here we have lot of holes lot of you know equal number of N_A^- also. Similarly, here you have lot of electrons, an equal number of positively charged N_D also; so these are all balanced.

So, the total number of electrons here is equal to exactly the total number of N_D^+. So, it is charge neutral here also is charge neutral, but there is a field here, that field will now oppose, that field will oppose and make sure that no more holes can come. That field will also oppose and make sure that no more electrons can come; so it is now in equilibrium; it is now in equilibrium ok; there is no current flowing.

Initially, when they combine you might think that there is some kind flowing, but there is a very quick process, very little bit of electrons and holes have moved and basically balance and now there is no actually there is no current flow on; so this is equilibrium that has formed.

Now, we have to be more careful in trying to understand each and every step will happen here.

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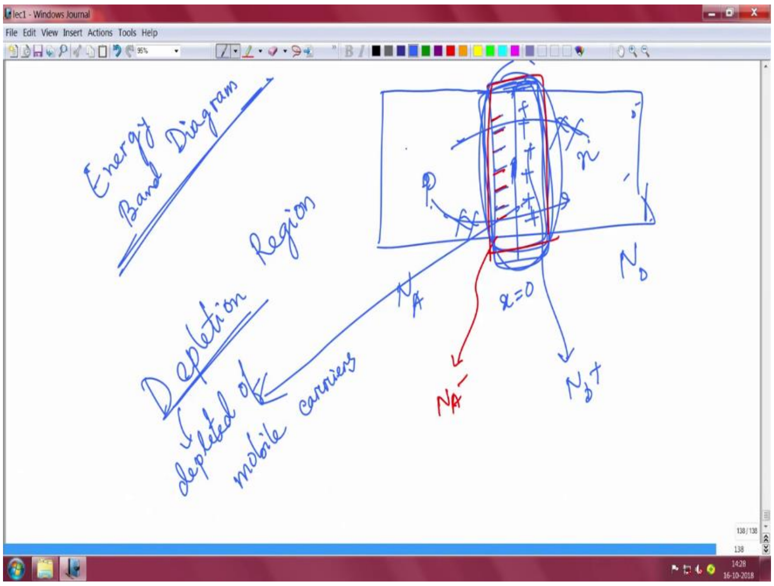

So, for example, this was p type so; that means, there is a N_A that we have doped here. And you know this was this is the junction, this is x = 0 this is very long junction there is; so this is very large and this is N_D doping that is here; so it is a n type here.

Once you holes move from this side to that side and they are recombined near the junction, what will leave behind here; when I say this is the junction that has formed here what leaves behind here is negatively charged ionized cores; N_A^-. This N_A^- is also here, but those are balanced exactly by the holes that are there; the holes that are there.

Similarly, there are N_D^+ here but those N_D^+ are balanced by electrons that are here. So, it is all in equilibrium anyway, but over in this area in this entire; I mean in this area, in this area, the mobile electrons and mobile mobile holes have recombined and they have vanished ok. So, what has left behind is a negatively charged ionized core here and here they have left behind like a sheet of positively charged dopant here; there are no mobile electrons, there are no mobile electrons.

So, this region that has formed and there is a field here now I keep telling you; there is a field here which will oppose any movement of electrons and holes from either side to other side. Electrons from here to here, they will be blocked and holes from here to here will be blocked. So, this particular around region that has formed, that is called depletion region; why is it called depletion region? The word deplete means that there is nothing, it is depleted. When you say that particular you know area is depleted of mineral resources; it means there are no mineral resources in that area.

When you say that lake or that river is depleted the water; it means there is no water. So, when I say this is depleted depletion region, it means this is depleted of carriers; mobile carriers ok. Depleted of mobile carriers; what are mobile carriers? Mobile carriers are electrons and holes; so, electrons and holes are not there because they have recombined; what has remained there is immobile negatively charged and immobile positively charged core.

This region, this region has no free electrons no free holes and any further movement of free electrons and free holes from both sides are blocked. So, this region is called depletion region because this is depleted of carriers. There are absolutely no mobile carriers here, that is the approximation; it is called the depletion approximation and there will be a field here now ok.

Now, how will in this; in this once you have join this thing and you understand that this is formed, how will the energy band diagram look for the same? Remember, energy band diagram; conduction band valence band from a level. How will the energy band diagram look for this? That will tell us exactly many of the things that we want to understand in the p-n junction ok.

So, we will take up that in the next class. So, here we will wrap up the today’s session here and the interaction of p-n junction, right. And we had introduced p-n junction and before that we have solved examples of continuity equation if you remember; now we have introduced the concept of depletion region and how electrons and holes diffuse and they recombine and so on and so forth.

Next class, we shall actually try to draw the energy band diagram of the p-n junction. And so many things will become clear the moment we draw energy band diagram. The conduction band valence band, Fermi level if you recall, we will join that diagram from p side and n side and see what happens ok. So, we will end up the class here.

Thank you for your time; we will catch you in the next class ok.