Semiconductor Devices and Circuits
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Lecture - 16
Recombination and Generation - Continued, Charge Transport

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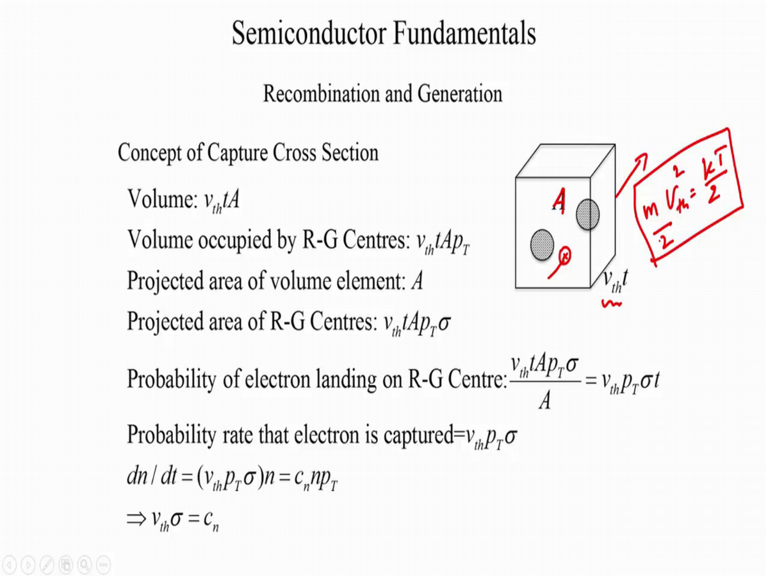

We have two more topics to discuss in this with regards to Recombination and Generation. And the first is something true with the Capture Cross Section. So, this is an order is not a new concept that is going to change things that we have learnt, but it is a different way of viewing the R-G capture and it is a very geometrical method of viewing the capture of electrons in R-G centers and the argument for this goes like this.

So, let us say you have a volume in a semiconductor ok. So, were looking at the actual physical picture in a semiconductor and this volume is going to cross section A and an electron is sort of traveling through this cross section it is going through this ok. So, let me draw that better. So, the electron is actually traveling through that.

And let us say the electron has got a thermal velocity V t h and V t h is what it is k T by 2 because it is just one dimension here and m V square by 2. So, that is the relation that is dictating what is V t h; it is got some thermal velocity. And therefore, in time t the electron would have travelled a distance of V t h by t.

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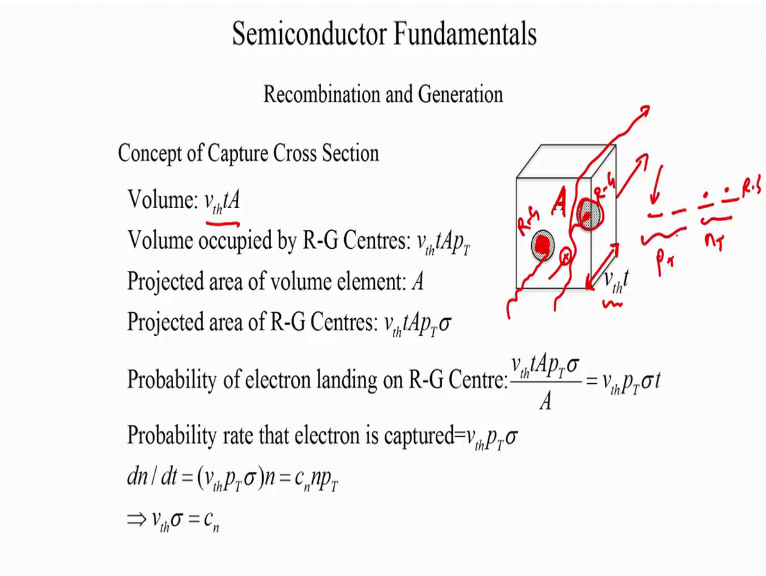

So, let us look at this volume which is got an area of cross section it is a cuboid which has got an area of cross section A and it is got a thickness or you know the depth is V t h into t. So, the volume of this cuboid is V t h into t into A and inside this region of space, you have some R-G centers.

So, these are all R-G k centers that can capture electrons and these centers have got a capture radius. So, if an electron where to move inside here, it is definitely captured; it is trapped and if it does not, if it can escape all these centers then the electron is not trapped ok.

Therefore, the since these centers for capture have to be empty states ok. So, we have the R-G states some of them are filled; some of them are empty and it is only these states that can capture electrons ok.

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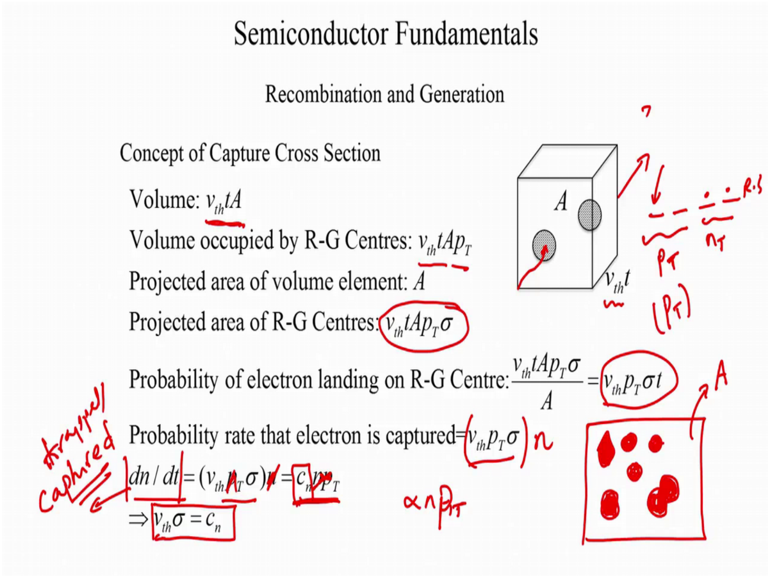

So, the number of capture sites inside this volume is P T which is the number of capture sites per unit volume into the total volume under consideration. So, the total volume under consideration is V t h into t into A and that volume occupied by the capture sites is V t h into t into A into P T. P T is a number per unit volume.

Now, let us project this entire three d structure onto a 2 D plane. So, we sort of squeeze in we flattened out all the R-G centers. So, you have the R-G centers here, they might have been to say behind one another and you know these are all regions occupied by the R-G centers and this entire area has got an area of A and the total area, the total projected area as seen through all these R-G centers is the number of R-G centers to some extent into the cross section area of each R-G centre ok.

So, we will define this cross section area; this is the area within which if an electron were to enter, the electrons were to be captured. We will define this cross section area as sigma. This is the number of R-G centers and if these R-G centers are seen independently that is there is no intersection between them.

The projected area of all the R-G centers is essentially this and this sigma can sort of take an effective value. So, if there is a lot of intersection between these R-G centers as we project them. So, let us say it is a very nice geometrical concept. So, let us say there were 2 R-G centers just one behind the other and they appear like this in this projection. So, sigma could take an effective value ok; need not it can be defined the little differently.

So, essentially what we are talking about here is that this area represents the shaded region which are all the capture zones and A is the total area and an electron is going to go through this region and it is going to go through at a random point.

So, what is the probability that the electron is captured? It is a probability that the electron lands on one of these shaded regions which is V t h t into A p T sigma by A which is this term here. What is the rate, the probability rate that the electron is captured? It is the time derivative of that which is simply this term. Now, the probability rate times the number of electrons per unit volume is essentially a measure of d n by d t ok.

So, d n by d t; then becomes V t h into p T into sigma into n which according to our old definition was c n n into p T. So, if you remember of many slides back, we said that the rate at which electrons are captured. So, this way this is only capture. So, we are not saying d n by d t, there is only capture of electrons rated which they are captured or trapped.

We had said that that was proportional to n into p T and we gave a proportionality constant called c n for the electron capture. So, we are talking about the same derivative here. Therefore, these two terms are the same which implies that we get a geometrical insight into what c n is. So, you see n and p T can be cancelled and therefore, your c n is nothing but the thermal velocity into sigma. So, it is the same concept, but it is a very geometrical way of viewing the same idea. Now, the final topic in on that we will study that we will study under Recombination and Generation ok.

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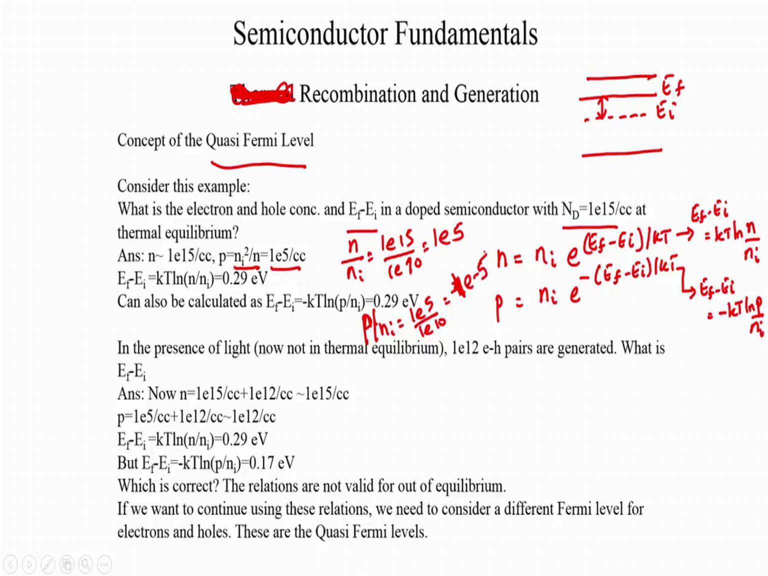

So, this is a typo, there is no thermal that I am sorry quite a bit of quite a few typos and this topic; please do bear with me.

The final topic that we will study in recombination generation is to do with the concept of Quasi Fermi Levels ok. As this is a concept that we will not be using quite a bit, we will not we will not really use Quasi Fermi Levels through the course. We will manage it without using this concept, but it is a concept that you need to be aware of and I think its best discussed with the example, with a with an example. So, let us say you have an N type semiconductor equilibrium ok.

So, N d is 1e15 that is the; it is N type semiconductor. Therefore, the donor concentration is 1e15 per cc and they are asked to locate E f minus E i. So, we had an intrinsic semiconductor that was E i, the intrinsic fermi level and after doping it N type, the fermi level moved closer to the conduction band and we want to calculate what this is.

Now, there are two methods to calculate it because I know that n is equal to n i e to the power E f minus E i by k T and P is equal to n i e to the power minus E f minus E i by k T. Therefore, if I use this approach my E f minus E i is equal to k T ln n by n i and if I use this approach my E f minus E i is equal to minus k T ln P by n i. So, let us see what both these approach is giving?

Now, n i let us say is about 1 e 10 which means my n since its doped and since now the dopant concentration is much larger than 1 e 10, we will say n is approximately 1 e 15 per cc and P according to the Mass action law it is all at equilibrium. So, therefore, according to the Mass action law, it is n i square by n which is 1 e 5.

So, if we were to plug in n by n i. So, n by n i is 1e15 by 1e5 1e10 which is 1 e 5 and what is n i by what is P by n i? P by n i is 1 e 5 by 1 e 10 which is minus, I am sorry 1 e minus 5. So, you plug in these two values here, we will find that both these options give you the same answer and you will find that E f minus E i is approximately 0.29 electron volts.

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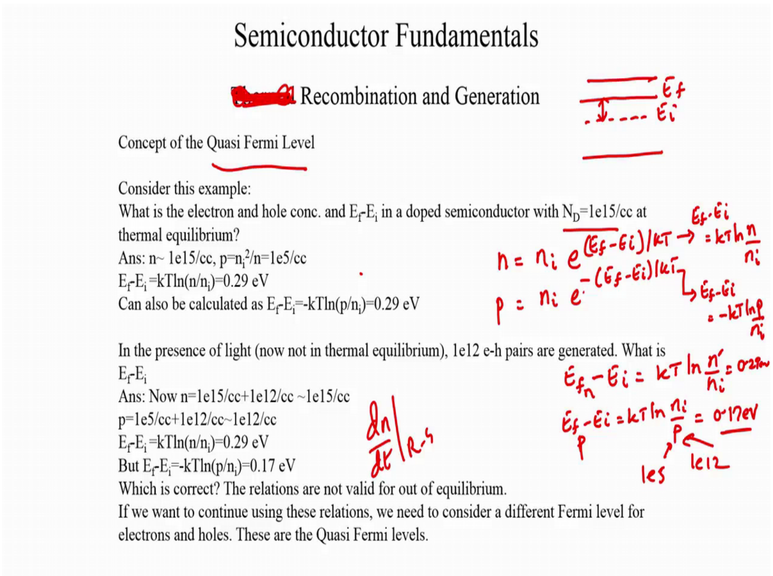

Now, let us take this semiconductor out of equilibrium ok. So, let us say we throw some light on the semiconductor and we generate 1 e 12 electron pairs electron hole pairs.

So, what is happened to the carrier count now? Now, n was initially 1e15 at equilibrium, we have now added 1e12 carriers and therefore, 1e15 plus 1e12 is approximately 1e15 because the amount of injected carriers about is about 1000 times less than the equilibrium carrier concentration. On the other hand, p was only 1e5 per cc in equilibrium and now you have added 1e12. So, therefore, we have made a significant change in the count for p. So, p has now become 1e12 per cc. So, although n remained the same, P has suddenly changed.

Now, let us try to calculate E f minus E i. We will use both these approaches. Now clearly you can see that there is going to be a problem because the E f minus E i calculation sorry. E f minus E i calculation using the electron count has not changed because n is still 1e15, but the E f minus E i calculation using holes has to change significantly because the hole has now gone from 1e5 to 1e12. So, this used to be 1e5 for cc, but now because of light being through on it, it will become 1e12 and you will end up with a very different terms; so, you will end up with 0.17 electron volt. So, which of these is correct ok? So, there is this seems you were paradoxical.

So, therefore, when we discuss non equilibrium conditions ok, we cannot allow a common fermi level for electrons and holes. It cannot be the same. Therefore, the electrons now take a fermi level called E f n which is the quasi fermi level for electrons and holes tickle fermi level called E f p which is the fermi level for holes and therefore, we must rewrite these equations we cannot use one common E f.

Therefore, E f n minus E i is 0.29 electron volts which means the quasi fermi level for electrons is still very much the same as the fermi level at equilibrium. But the quasi fermi level for holes has shifted from the equilibrium fermi level value ok. It is now only one 0.17 electron volts above your E i or you know yeah ok.

So, this is the idea of quasi fermi levels and this is something that we will not use, we will not be using this concept, but although it is useful to know, it can be a very powerful tool while performing calculations, but we will try to avoid it ok. So, with this, we come to the end of the study on Recombination and Generation and we now have the tools to understand how d n by d t is affected by recombination generation mechanisms ok.

And we will now embark upon establishing a concept or an idea which is called as the continuity equation or a complete budget of the carrier counts in the volume which is the big picture we have been discussing and we will use that to study semiconductors in various conditions.

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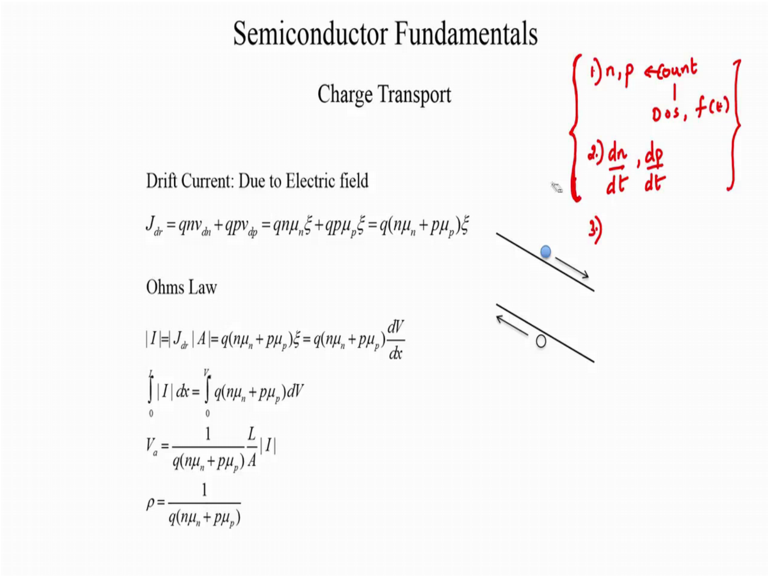

So, we now consider mechanisms of charge transport ok. So, far if you make us if you take a summary of everything we have done, we have established method to count the number of carriers in the conduction band and the number of holes in the valence band. So, we can count them and in order to count them, we established what the density of states was; we established what the fermi function was and with these two, we could evaluate the values of n n p. Then, in the generation recombination processes, we saw how the count through the dynamics of the electrons in the conduction band and the hole holes in the valence band is influenced by the various features.

So, now we are trying to establish the concepts of charge transport. So, these are the mechanisms by which the electron and hole concentrations could vary and now based on these variations or based on these counts of electrons and hole concentration, we want to establish what the currents would be in a semiconductor and the different mechanisms of charge transport in a semiconductor. So, we are gradually heading towards something called as the Continuity equation which is a very very useful concept and a useful idea in order to solve out the reaction of the semiconductor for various situations. So, let us focus on two most important methods of charge transport ok.

So, we have already come across one phenomenon which was called as Tunneling ok.

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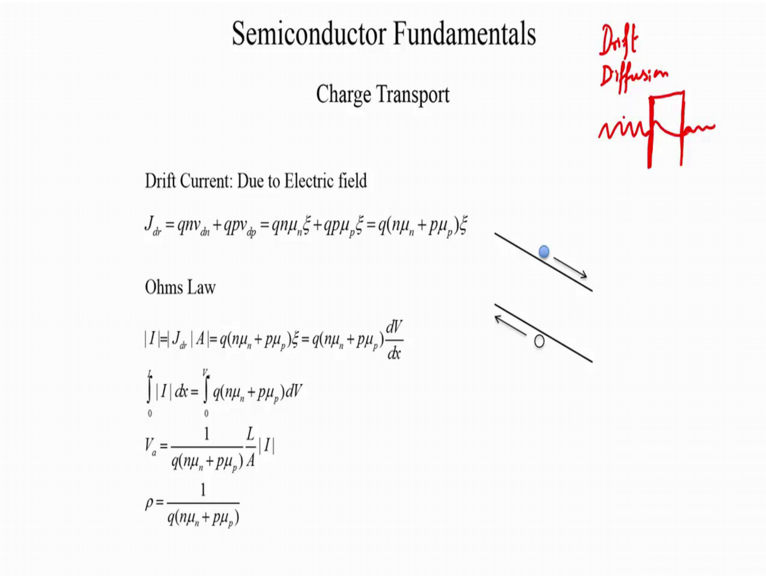

So, we will skip that for now. We have we are not interested in tunneling in this particular discussion. We are interested in two particular modes of charge transport and they are called as Drift and Diffusion ok. So, Drift and Diffusion and in a very little while, I will explain to you what these two terms imply ok.

Now of course, there are other methods of charge transport and I think the most prominent one is a tunneling which was a you have the wave function of the electron on one side of a barrier and the wave function does exist on the other side, simply because there is a non-zero probability that the wave function can pass this barrier, despite the energy of the electron the energy of the carrier being less than the barrier height.

We have already looked at this in a brief discussion and quantum mechanics and we will use we will use the concept of tunneling later on, but it is not the focus of this particular study.

So, first let us look at the Drift current ok.

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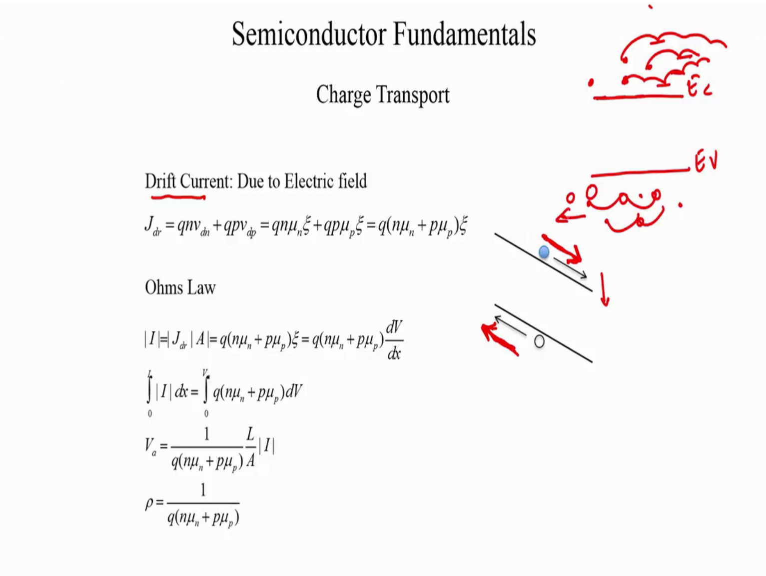

Now, what is Drift current mean? Drift current simply means that your electrons and holes are moving through the semiconductor because of the presence of an electric field. So, you have a semiconductor, you have your let us say you have your conduction band, you have your valence band and you have free electrons in the basically the electrons in the conduction band and you have holes in the valence band.

And the moment you apply an electric field, what would happen is these bands would actually bend ok. I have shown here and all the electrons would run downhill and the holes would run uphill ok. So, that is the way we the energy band diagrams are drawn to define the lower the lower side if you might allow as having the higher potential. So, all the electrons would run towards the higher potential side and all the holes will run towards the lower potential side.

So, this is the response to the electrons and holes to an applied electric field. So, essentially what this requires is you need to have free electrons in the conduction band and there are empty states and these electron sort of move through these states; whereas, the electrons in the valence band move through these vacancies which essentially gives you this picture of the holes moving towards the other side ok. So, that is what is happening when you applying electric field through a across a semiconductor.

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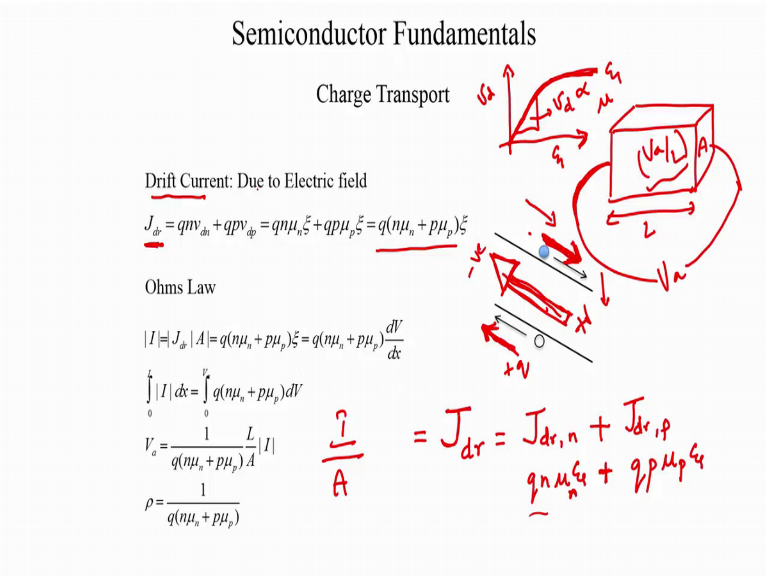

So, in order to get a quantitative estimate as to what the drift current is; if you think of the semiconductor ok. So, you have applied an electric field, let us say the area of cross section is A and let us say the semiconductors got a length capital L and let us say we have applied and a voltage V a cross this ok.

Now, as long as the electric field, we which we will sort of write down as V a by L ok. So, may not be perfectly correct, but for all practical purposes for the time being we will just say it is V a by L. It is a very uniform electric field there is nothing else inside and we have a field of V a by L. So, the electric field in the semiconductor alarms the electrons and holes to move to the opposite electrodes.

Now, the electron flux ok. So, if you look at the current density and we will say that the drift current density has got this what is a subscript d r as this written here; the drift current density, the total drift current density is the drift current due to electrons and the drift current due to holes.

Now, do these two current sum or take a difference ok. So, if you apply electric fields, the holes which are positively charged run in the opposite direction as that of the electrons and therefore, these two currents sum up to give you the total drift current. Now, what is the drift current due to electrons? It is the total charge per unit volume. So, we are talking the drift current density. So, this is the current per unit area ok. So, we are talking about I by A.

So, this is nothing but the total charge of free electrons per unit volume. So, n is the number of electrons per unit volume that is in the conduction band. So, which is a free electron concentration; q is the electronic charge and if a q n is the total charge of the electrons that are responding to the applied field into the drift velocity of the electrons.

So, this gives you this gives you a measure of the distance covered by the electrons per unit time and therefore, these two terms together is nothing but the rate of change of charge per unit area which is nothing but d q by d t, where this all taken as a per unit area estimate ok. So, that is the drift current due to electrons ok. So, you have q and V d n and similarly for holes you have q p V d p; where, V d p is the drift current due to the applied electric field.

Now, we have already looked at the concept of mobility of carriers and we did notice that in the presence of a low electric field. So, you have you have the electric field and you have the drift velocity of the carriers; at low electric fields the drift velocity is linearly proportional to the electric field and then, it sort of saturated out in some of the semiconductors.

So, at low electric field, the relation between the drift velocity and the applied electric field is given by V d s proportional to the electric field with a constant of proportionality being the mobility of the semiconductor. So, therefore, they can rewrite the drift velocity of the electrons and holes as q n mu times the electric field or mu n times electric field; where, n mu n is the mobility of the electrons and q p mu p into electric field; where, mu p is the mobility of the holes.

So, the summation of these two terms gives you the total current or the total current density due to drift and this is a very useful relation keep in mind, where in the electrons and holes contribute to the current together. So, certain points to note here; so, one the first thing is you might wonder what happened to the electron charge being negative ok. So, well that is already taken into account because the electrons and holes are moving in the opposite direction. So, if you are going to look at the conventional current ok. So, we are talking about the current in the opposite direction of the electrons.

So, the electron flux is one way, the current is always the opposite side that is the way current is defined. It gives the it is from the positively charged electrode to the negatively charged electrode and therefore, the current is in the same direction as out of the holes and since, the electrons have got negative charge and are moving in the opposite direction it is equivalent to having a current of plus q and mu an electric field in the opposite in the direction of the current ok. So, this is the relation between the drift current density of electrons and the drift current density of holes and the summation being the total drift current.

Now, this essentially leads to the formulation of Ohms law ok. So, for example, let us let us look at the total current ok.

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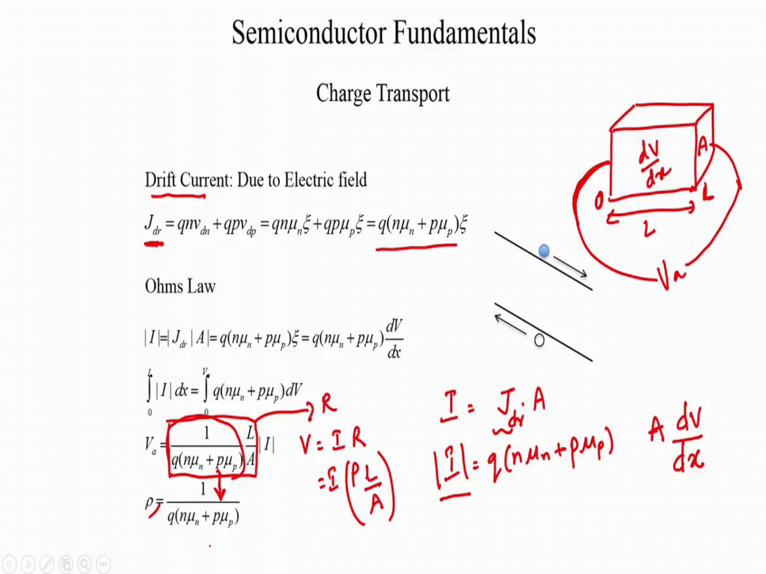

So, we have the total current through the semiconductor being J times the area and we already know that the current per the drift current density ok. So, we are only interested in the current due to the applied, current due to the applied voltage and the drift current dense the drift current density is nothing but q and mu n plus p mu p into the electric field into the area gives you the total current.

Now, the electric field is nothing but your d v by d x ok; you can throw in a negative sign, but we are interested in the magnitude of the current because in the in the case of in order to derive Ohms law. I really would not establish a relation between the voltage the current and the resistance of a resistor. And therefore, the direction of the current is not really a matter of concern right now ok. So, therefore, we will not worry about the electric field being minus d v by d x; we will just say d v by d x and instead use the modulus of the current ok.

So, this happens to be the current through the device. Now if you just solve this differential equation. So, as so instead of V a by L which is the very liberal way of defining electric field, we have defined the electric field more carefully as d v by d x ok. So, B by L is a very liberal way of defining the electric field, particularly when a semiconductors involved; as you will soon see ok. So, that is that is probably true for an insulator, but not so true for a semiconductor. So,.

So, let us define let us define the current versus voltage in this particular manner. So, if you solve this differential equation and you integrate, you integrate the current with respect to d x and as you go from one end of the semiconductor to the other. So, let us say you go from 0 to L the voltage varies from 0 to V a and by just solving this differential equation, you find that your V a is nothing but 1 by q n mu n plus q p mu p into L by A into I ok. So, this is the relation between the applied voltage and the deep current through the device.

So, what does this remind us off? So, this term here is the resistance. So firstly, it tells us a thick the current voltage have a linear relation. So, the voltage is equal to I into R and this R has got a term which is equivalent to the resistivity. So, this particular term is the resistivity, where R is a rho L by A. L and A defines the geometrical parameters and most importantly rho is the resistivity that is 1 by q n mu n plus p mu p.

So, the resistivity of a material is taken to be a constant ok, but now we know what that constant depends upon. It depends upon the it depends upon the mobility of electrons in the mobility of holes and the total electron concentration per unit volume and the hole concentration per that is the number of holes per unit volume. So, in a metal, you do not have holes and therefore, the resistivity is simply 1 by q n mu m all right. So, that is Drift current. So, it is a response of the carriers to the applied electric field which is obtained by applying a voltage across the device.