Fundamentals of Semiconductor Devices

Prof. Digbijoy N. Nath
Centre for Nano Science and Engineering
Indian Institute of Science, Bangalore

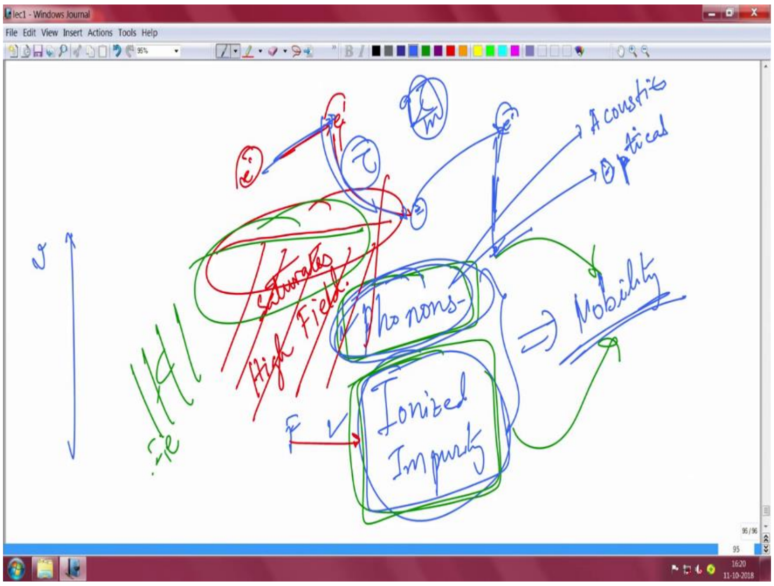
Lecture – 11
Low-field and high-field transport, introduction to diffusion

Welcome back. So, if you recall the last lecture we had ended with the introduction on mobility, what is electron and hole mobility and how does it depend on effective mass, we wrote down the expression of mobility and also we try to discuss what physically it means, it is the slope of the velocity and field characteristics. So, if you accelerate by playing more and more field an electron will move faster and faster, that slope of how fast it is moving the velocity with field is called mobility.

So, I told you that mobility is a very important concept because mobility dictates how much current can flow and how much current flows will also decide how the device performs and mobility depends strongly on temperature. So, if you cool down a device or if you heat up a device, mobility will change and that change will also affect the current that is flowing and that will affect the device that is working, hence you always have a range of temperature over which you can operate devices. The other important reasons for the temperature limitation regarding from the circuits point of view, but fundamentally from a device point of view the mobility is very sensitive to temperature.

An electron or hole mobility is a very important parameter in understanding devices that will always come ok, many things are tied together I told you know drifts the term drift and diffusion or something we are using although we have not extensively discussed that something we will also discuss. So, we will resume this lecture with what we left and that is you know the definition of mobility and how to interpret mobility in the terms of temperature dependence.

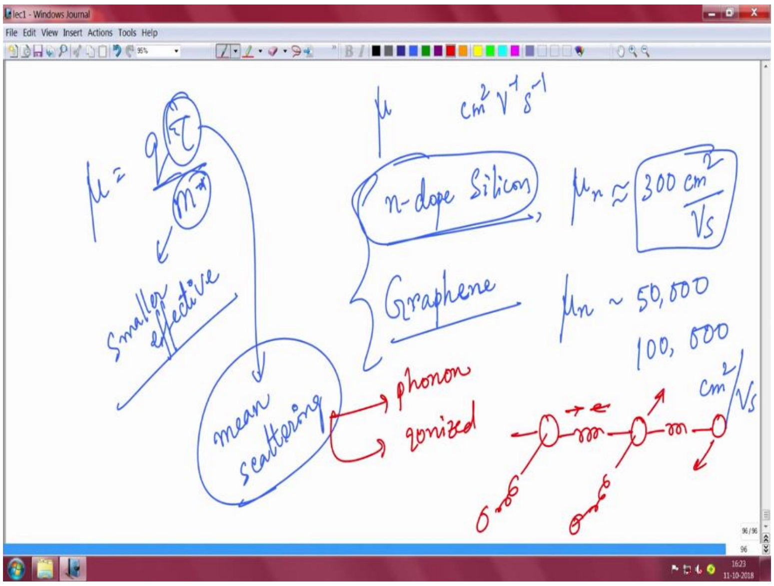
(Refer Slide Time: 01:57)



So, we will come through whiteboard again if you recall from the last lecture I told you, that a mobility depends a very strongly on phonons which is the vibrating atoms, there are different kinds of vibration I told you acoustic and optical, their branches actually of phonon vibration or sorry acoustic and optical. And acoustic and optical phonons are essentially two sort of a branches two ways in which atoms can vibrate they affect a lot how the electrons mobility the value of electrons mobility and also ionized impurity it can scatter electrons and that is why they affect the mobility.

So, these are the two things now we will see how their effect, you know translates into a temperature dependence sort of a thing from mobility.

(Refer Slide Time: 02:41)



I told you the unit of mobility we denote it with μ and a unit is a $cm^2V^{-1}s^{-1}$ ok, what is what are the typical values of mobility for example, if you take an n type doped silicon a moderately n type doped silicon, then your electron mobility μ_n would be approximately you know around say 300 $cm^2V^{-1}s^{-1}$ hole will be much lower.

Ah if you also take other semiconductors the mobility value might be much larger much slower much smaller you know for example, you have probably heard of the word graphene, Graphene, the exfoliation and the synthesis of graphene had gotten the Nobel prize in physics in 2010 to Novoselov and Geim of England.

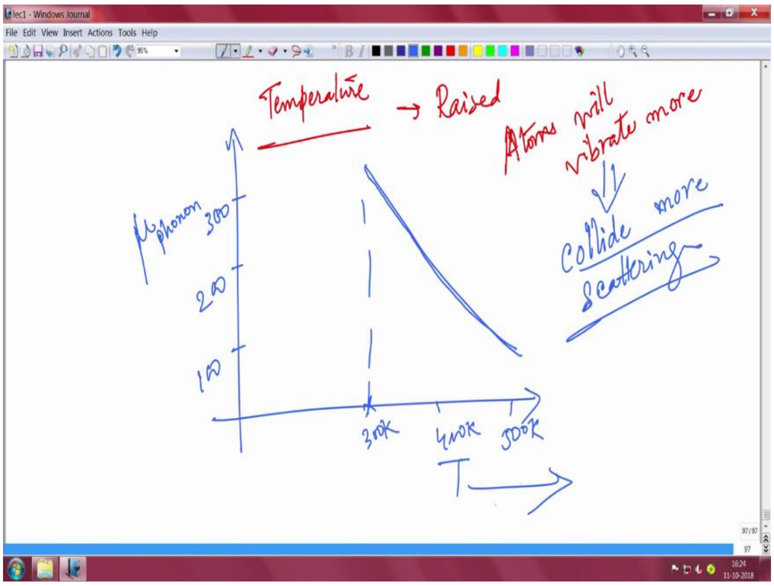
And graphene is like a 2 dimensional sheet of one sheet of carbon atoms electron mobility in graphene can be very high, it can be if I call correctly something like 50000 or even like 100000 or even more centimeter square per hole second, the other way is we can also even go upto probably million you know if you suspended a graphene, but also other things. So, you know it depends on the material very strongly.

So, in silicon typically which is what we are going to discuss this, the devices in this course, you have a mobility of say around 300 it depends on also temperature. So, this is a good number we should keep in mind and hole mobility will be smaller, if you recall mobility depends on the charge times of scattering time and the effective mass.

So, if your effective mass becomes smaller your mobility becomes larger. So, you want the smaller effective mass material, if you have a smaller effective mass then your mobility will become better that is a good indication, if your effective mass is high your mobility will become low. And its scattering time this is your mean scattering time or we can say the yeah the men collision time, this mean scattering time in a way in a very simplistic way the time between two adjacent collisions. This mean scattering time depends as I told you on phonons and on ionized impurity.

So, I told you phonons are nothing but vibrating atoms we have the two different acoustic and optical modes, you know actually how we define acoustic and optical is I told you we can think of atoms as like they are spring, essentially it is you know they are vibrating atoms. You can also talk about two dimensional that's another thing though, but even if you talk about one dimensional you know string of atoms, they will vibrate either they can vibrate this way or one can vibrate this way one can vibrate this way. So, there are different ways in which they can vibrate right they can vibrate out of phase in phase. So, that is why these things come. Let us not go into the details of that, but let us see how you know temperature affects mobility.

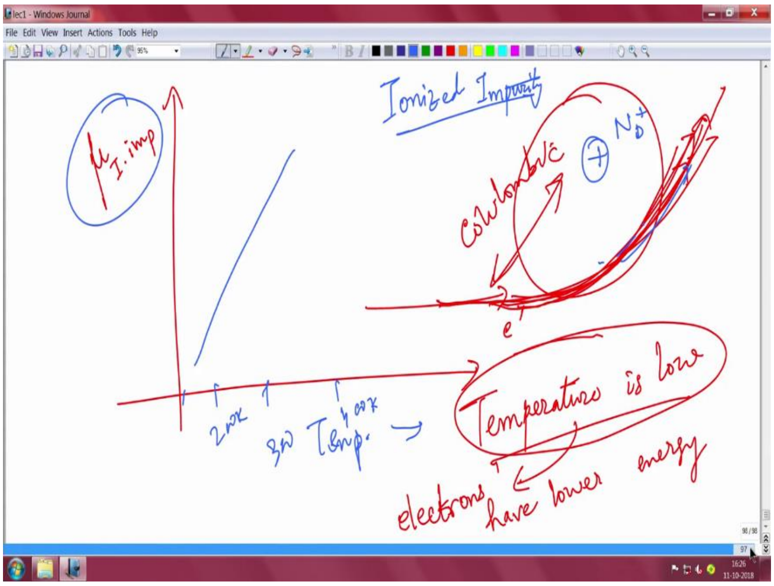
(Refer Slide Time: 05:13)



How temperature affects mobility? So, if your temperature is you know raised if your temperature is raised, then atoms sorry then atoms will vibrate more right atoms will vibrate more, if your temperature raises the atoms will vibrate more, if your atoms vibrate more, then they will they will scattered a electrons more or electrons will collide more. So, the scattering of the electrons will be more and more will be really more and so, the mobility will come down so, if I am plot mobility purely because of phonons only because of phonon for example, and with respect to temperature ok, if you are increasing temperature your mobility will come down.

Suppose this was 300 this is 200 this is 100 this may be say room temperature which is 300 Kelvin, this may be 400 Kelvin this may be 500 Kelvin and so on. I am just giving a qualitative sketch the values need not be accurate here, what I am saying is that as we increase the temperature your mobility, because of phonons will keep coming down, because as you increase the temperature as we increase the temperature in this direction, you have more scattering because your atoms are vibrating more they are going to collide you know the electrons are going to collide more they will scatter more ok, let us keep this picture in mind.

(Refer Slide Time: 06:39)

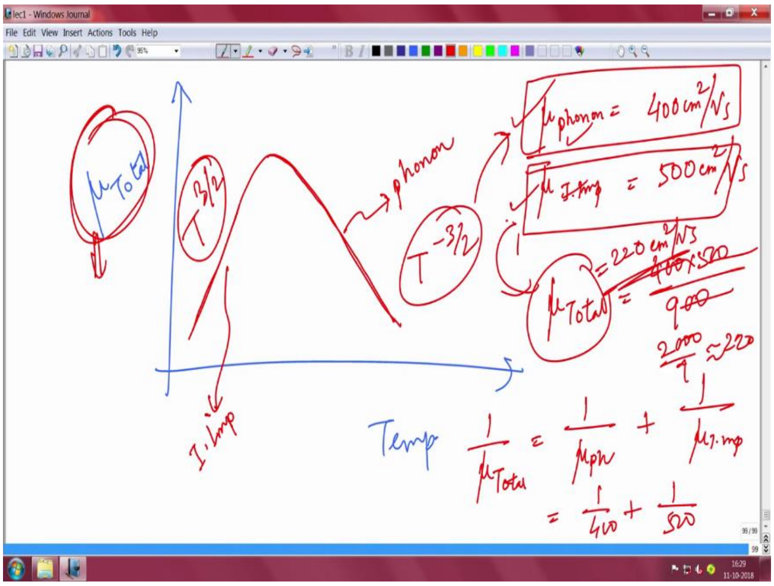


Next ionized impurities scattering, I told you ionized impurity scattering works by the fact that if you have say N_D^+ a positively charged ionized impurity and electron was moving in this direction this, because of the Coulombic force because of the Coulombic force your ionized impurity will set up a potential that will scatter that will perturb the electron path like this ok, that is how its scatters and it does not physically collide per say.

So, if the temperature is low if the temperature is low what will happen; that means, electrons have lower energy if the temperature is low electrons have lower energy. And if electrons have low energy then they will spend more time in the vicinity of this ionized impurity. In the vicinity of this ionized impurity they will spend more time or they will take more effort to overcome this Coulombic force sort of if you increase the temperature, the electrons will have more energy they will have to spend less time here, they can overcome this scattering more. Which means if I decrease or lowered a temperature, then electron will spend more time around it and it will scatter more which means the mobility will come down when temperature is lowered.

So, if I plot mobility purely limited by ionized impurity, then this is temperature on the x axis 300 Kelvin maybe 400 Kelvin this is say 200 Kelvin; we and you know and you keep decreasing 10 Kelvin and so on, then with this impurity limited scattering this mobility will reduce when your temperature is reduced why because at lower temperature electrons have low energy. So, they will not be able to overcome this columbic potential. So, well they will have to spend more time. So, mobility actually falls down its lowering temperature. So, it goes like it goes something like this. So, you see impurity ionized impurity scattering goes like this and your phonon scattering goes like this.

(Refer Slide Time: 08:53)



So, the total scattering will therefore, go how the total mobility not scattering the same thing actually the total mobility, because of both ionized scattering and phonons you know scattering with respect to temperature will therefore, have a shape like this it will go up and then come down. One of them is limited by a phonon at high temperature at low temperature it is limited by ionized impurity.

This total mobility is actually the mobility that you can experimentally measure this is the net mobility that you can experimentally measure. So, this is the total mobility of the electrons or say holes. And typically in silicon this should ideally fall off in the range of $T^{-3/2}$ and this should rise up in the range in the way of $T^{3/2}$, there are some theory and experimental data to sort of support this claim.

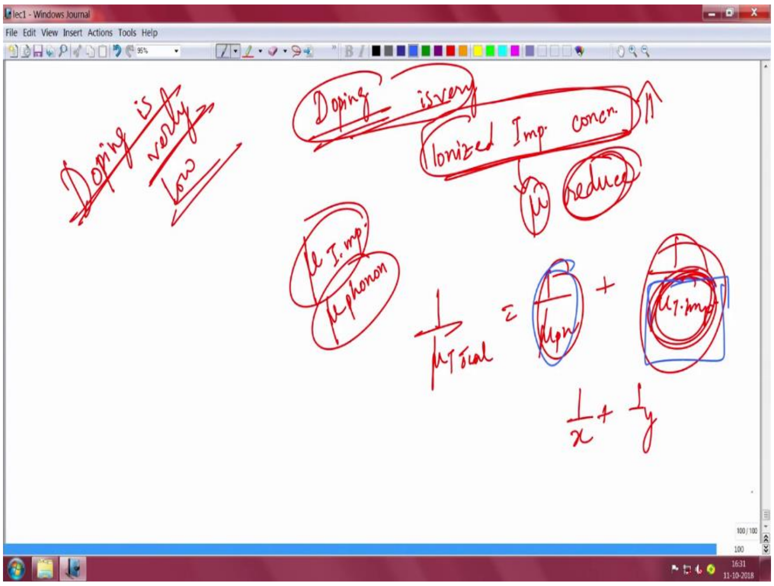
But, it may not be exactly 3 by 2 because of many impurities and many other imperfections in the crystal and so on, but loosely speaking this should be the trend. This should be the trend and you should remember that actually the total mobility suppose the mobility because of phonon only is say you know 400 $cm^2V^{-1}s^{-1}$ sorry.

And mobility because of ionized impurity purely is suppose a 500 $cm^2V^{-1}s^{-1}$, this is a mobility purely because of phonon purely because of ionized impurity, then that total mobility that you will actually measure in the sample you cannot be measure it is directly you know generally so, easily what you measure actually is the total electron mobility it depends on both these and this it is not a summation of both of them it is actually

$$1/\mu_{Total}=(1/\mu_{pn} +1/\mu_{I.imp})$$

So, the total mobility will be 1/400 in this case + 1/500 and now you take the inverse. So, the total mobility will be (400 * 500) / (400 + 500). So, that will be your (2000 / 9) which is roughly 220 $cm^2V^{-1}s^{-1}$ so, this will be 220 $cm^2V^{-1}s^{-1}$ will be the net mobility, if your phonon and impurity limited mobility at this at a particular temperature. So, that is with respect to you know temperature.

(Refer Slide Time: 11:19)



So, for example, you know if I if I take a doping for example, you know doping also affects mobility by the way all this while we have been talking about sort of very moderate doping. So, very very moderate doping if your doping is very high if your doping is very high then ionized impurity concentration increases, you know your ionized impurity concentration will increase.

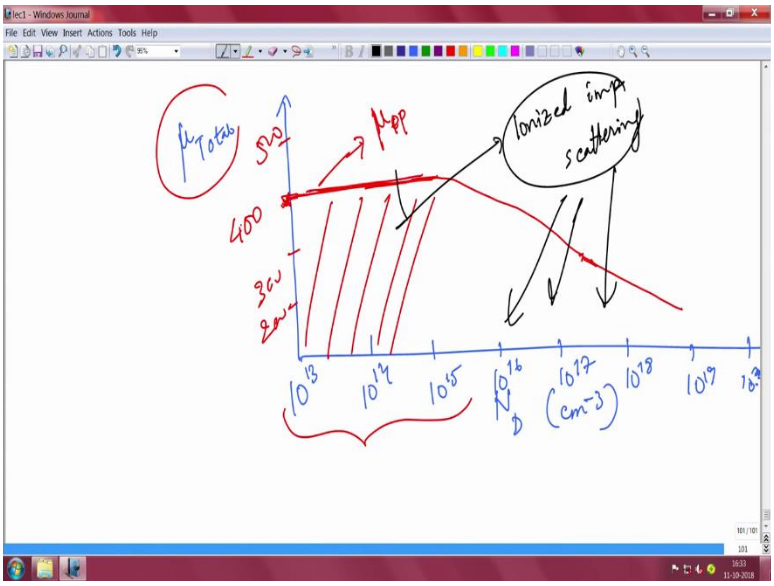
If your ionized impurity concentration increases with very high doping, then your ionized impurity scattering limited mobility will reduce and this will be the dominating factor, if your doping is very high than more than phonon more than phonon your ionized impurity scattering will be so high you have so high doping. So, your electrons will scatter more rapidly and more repeatedly and frequently from the high density of ionized impurity.

And if that is the case then the mobility due to ionized impurity will be so, low that phonon mobility will not be an important contributor. Remember $1/\mu_{Total} = (1/\mu_{pn} + 1/\mu_{I.imp})$. If this because of very high doping this ionized impurity - you know limited mobility might become very small and you know that, if you have $(1/x + 1/y)$, then the smaller of the two dominates in this thing right. So, this will dominate then this will not dominate enough.

And if your doping is very low if your doping is very low, then you know if your doping is very low, then your extremely low doping then your ionized impurity contribution will decrease and your phonon limited mobility will be the dominating mobility.

So, what that mean is that if I dope it very low than this quantity the ionized impurity limited mobility will be very large number, because it is not limiting it. So, that this will dominate right; so, that you should keep in mind.

(Refer Slide Time: 13:11)

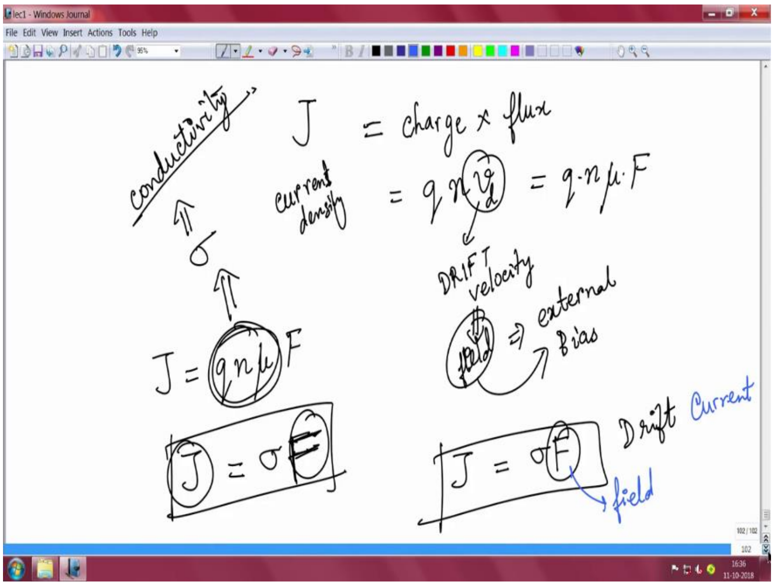


So, for example, if I do a suppose I plot the total mobility I plot the total mobility versus say doping N_D for n type semiconductor plotting doping suppose this is 10^{13} which is almost more doping in a way silicon I am talking about silicon 10^{13}, 10^{15}, 10^{16} probably 10^{17} ok, 10^{18}, 10^{19}, 10^{20} and so on this is the high doping by the way 10^{19} and doping.

So, the total mobility initially the total mobility because of both phonon and impurity scattering will remain constant initially, why because at lower doping your ionized impurity concentration is not so high. So, the scattering because of ionized impurity scattering is not going to be dominant factor it is very small I mean the mobility is very large. So, the scattering is very low and entire value here is dominated by phonon scattering and phonon scattering does not depend on doping more or less, but as your doping starts increasing your ionized impurity collision will now increase so much there it will start playing an important role. So, it will start decreasing eventually at 10^{18}, 10^{19} the mobility will decrease very much mobility will decrease very much. So, that is what is going to happen.

So, if I am giving a plot like this and the suppose this is value is 400, this is 300, this is 200, this is 500 then you know that this of 400 corresponds to purely optical phonon limited mobility ok, this is purely optical phonon limited, because in this range at low at low doping range your at low doping range your ionized impurity scattering is very infrequent or very the scattering is very weak they are not so much scattering. This scattering becomes important only at high doping or even moderate doping it will have some effect, but at very low doping it will probably not have so, much of effect.

(Refer Slide Time: 15:19)

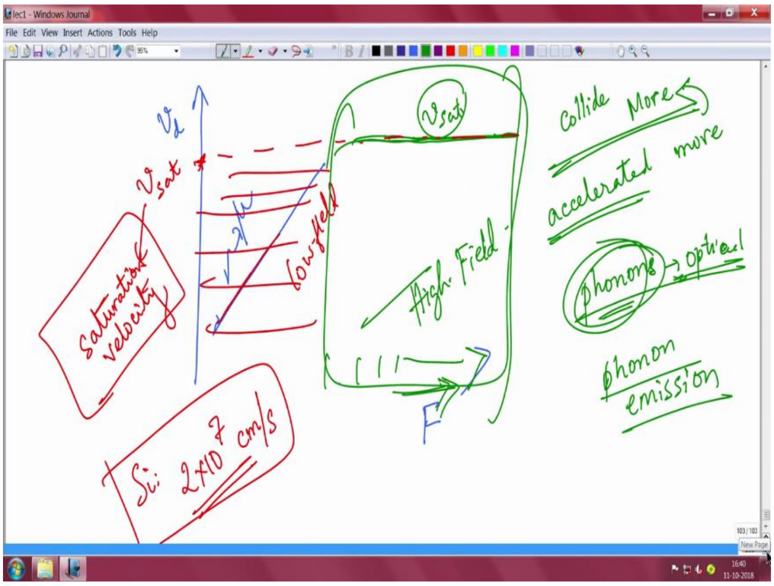


So, that we should keep in mind so, now we know mobility and if I mention current density this is current density. So, its normalized to area for example, current actually is nothing, but charge that you are carrying times the flux of the carrier that is flowing. So, charge of course, is q the charge of electron right and your flux is nothing, but total number of electrons that you have times the velocity with which they are moving. I told you velocity is in this case drift velocity and drift velocity this is drift velocity. And drift velocity will come only when there is a field in semiconductor like an n type dope semiconductor just a uniform semiconductor, this field that you need may come from external application external bias.

There may be cases like in p-n junction where a field might exists internally, but here I am talking about just the uniformly doped semiconductor. So, the drift velocity to come you need a field the field generally comes from external bias and now I can write q*n, I can write velocity as mobility times the external field. So, let me write again J=q*n*μ*F, this is field. This quantity is actually called σ which is called conductivity; conductivity of the sample. So, J=σ*F, you probably know this comes also from ohms law, field is actually your voltage by the length of the sample in a way.

So, you actually have a direct relation between the current and the voltage that you are applying its a linear relation comes from ohms law it also testifies ohms law, this is your current density that is proportional to field proportionality factor is called conductivity; σ= q*n*μ ok, it depends on mobility depends on the charge density if you remember and this is purely a drift current, because it depends on the field right this is the field, it depends on field and its purely drift current and drift current depends on mobility and charge as well as. It only exists when there is a field the field maybe externally applied, or it might also internally exist in the semiconductor. So, now mobility defines your field before I go to the concept of diffusion, we will rap up one last thing.

(Refer Slide Time: 17:51)



And that is I told you the velocity if I apply with respect- plot it with respect to field it increases linearly. So, the slope is called mobility I told you right. So, it cannot increase indefinitely after sometime it will saturate, it will saturate which means with increasing field the velocity is no longer increasing, but it has saturated at a value and that value is called v that is called v_{sat} or it is called saturation velocity.

And saturation velocity is actually a very important parameter of a material, saturation velocity is you know it is a very important parameter for a material silicon for example, I think has the self saturation velocity of close to $2*10^7$ cm/s, close to that maybe slightly lower than that ok, gallium arsenide might actually have more than this some other materials might have lower than this. So, depends actually.

So, the saturation velocity is very important and this will set a limit to how fast electrons will move cannot move faster than this ok, this I told you this region where the velocity and field having a linear relation is called a low field regime and the moment the velocity has saturated right, the velocity has saturated this region is called high field regime.

Now, what is the physical reason for the velocity saturation the velocity has saturated here, its cannot increase more than that the physical reason is that as you are increasing the field more and more you know this is the increasing field. As we are increasing field more and more the electrons or holes for example, are getting more and more accelerated they are gaining more and more energy, but eventually you know because they are gaining more and more energy they move faster and faster and they collide more also..

As if you are getting accelerated more if you are getting accelerated more, if I getting more energy from the field you also get collided more, you can imagine thinking of this like a like a vehicle like a car moving in traffic, if the car moves much faster it will also collide and have accident more and more with other vehicles on the road right.

So, if you accelerate a particle more and more it will move faster it will also collide more, eventually what will happen is that the rate at which the electron is gaining energy from the field will be, will be basically dissipated away to phonons to the vibrating atoms. The electrons that are gaining energy from the field will be dissipating away the energy to phonons particularly optical phonon; you know optical phonon is the type of phonon vibration.

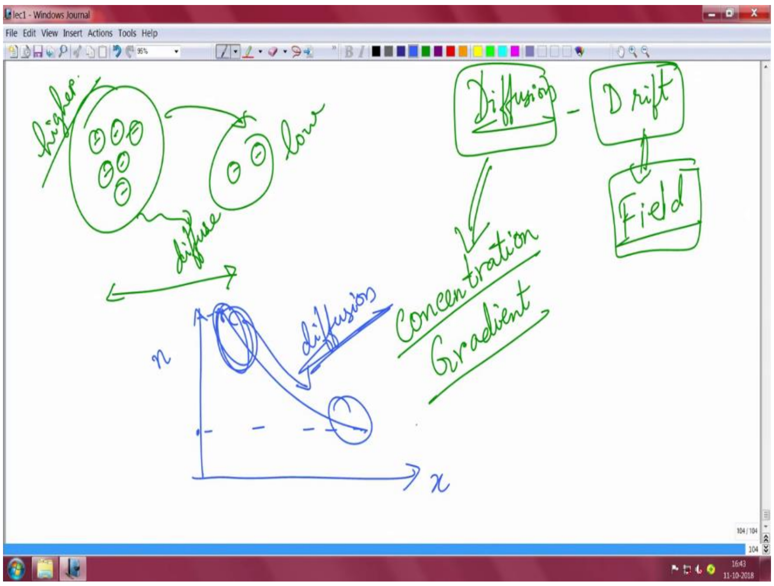
So, electrons that are gaining energy and getting accelerated from the field will now basically start dissipating a large amount of the energy to the phonons and so, the phonon scattering or we can say you know the fact that electrons are now giving away energy to the to the phonons will be limiting the velocity at which you can the maximum velocity you can achieve.

So, in the in the velocity saturation regime electrons are colliding so, much by getting so, much energy that it has put a limit. It has put a limit to the velocity it can go because it is starting to dissipate away that gained energy to the crystal to the crystal lattice to the vibrating atoms of the crystal lattice it is going to dissipate added energy. So, it cannot accelerate more that is why there is a limit of velocity saturation here ok, there is a limit to the velocity saturation here, semiconductors do display velocity saturation when metals do not display this velocity saturation, because the energy you need to achieve this velocity saturation in metals is so, high that it will actually melt the metal it will be so, high temperature eventually ok, because this it will heat up with so much of current that is secondary.

So, semiconductors do have a saturation velocity different materials have different velocity saturation, and when the velocity saturate we call its high field transport, because the field is very high. And the energy that the electrons are gaining remember the electrons that are gaining energy from the field are now losing the energy to phonon, it is basically dissipating the energy away to phonon, we call it phonon emission actually if you want to know the exact term it is called phonon emission which means electrons are giving away the energy to phonons ok, its they are giving away the energy to phonon they are no longer accelerating.

So, you should remember this term and its velocity you know and at high field transport comes in velocity sort of you know saturation regime. So, now, you know drift transport that comes in when there is a existence of a field and we will now come next come to a fact called a diffusion current.

(Refer Slide Time: 22:23)



So, once we have studied diffusion so, we have already studied drift and now we will study diffusion. So, drift and diffusion will basically complete our picture of electron transport and current flow. So, drift comes from field I told you already drift comes from field and diffusion comes from concentration gradient it comes from concentration gradient.

So, if there is a gradient of electron concentration, then there will be diffusion what do you mean by gradient there is a slope; that means, there is a higher concentration there is a lower concentration for example, if I spray a deodorant in one corner of the room after few minutes the whole room will smell the deodorant because the deos the spray molecules of the deodorant will now diffuse to areas, where there are lower concentration of the deos you know molecules.

So, if you have many electrons here too many electrons are here and very few electrons here for example, then under you know this normal conditions the high electrons will try to defuse from a region of higher concentration to a region of lower concentration, this is called diffusion and it is a natural tendency of even gas molecules and particles right.

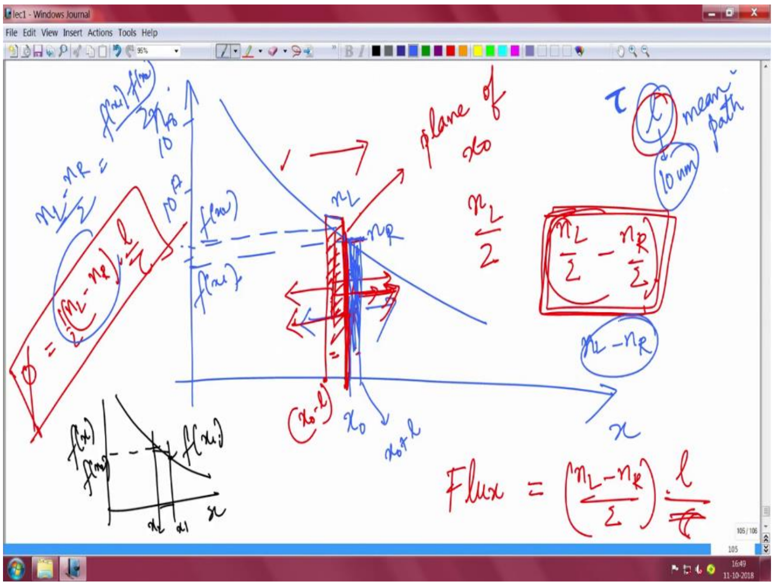
So, electrons will diffuse. So, concentration when they whenever there is a difference in concentration, whenever there is a concentration gradient there is there is going to be a diffusion current and whenever there is a field there will be a drift current. So, in ideal situation drift and diffusion might balance each other for example, like an p-n junction so in equilibrium you will not get any current, because although there is a field in some sometimes you know the diffusion might basically exactly balance the drift component and so on.

So, that is one thing that will come when you discuss p-n junction, but we should introduce the concept of diffusion. Now it is high time and you will find out the diffusion current actually depends on the derivative of the concentration gradient.

For example, I take electron concentration n this is n this is the total electron concentration I am plotting as the function of x; x is distance. So, electron concentration suppose electron concentration is constant like this, then there will be no diffusion because electron concentration is constant, there will not be any flow of electron because of concentration gradient there is no concentration gradient..

Now, suppose I have a concentration gradient like this which means electron concentration is high here. So, this is may be high electron concentration and this is electron concentration is low here. So, electrons will try to move from this region to this region by diffusion ok, electrons will try to move from the higher concentration region to a lower concentration region and we have to capture that mathematically. So, how do you do that; how do you capture the mathematical picture of diffusion you know?

(Refer Slide Time: 25:09)



So, for example, I take n and I have x, I take and this is the electron concentration for example, I take any point say x_0 and you know electrons collide and I am talking about a one dimensional picture. So, it will only have it can electrons can either go in +x or it can go in -x, there is no y and z direction excuse me.

So, electrons collide of course, they collide in all kinds of you know when they move they will collide in any direction, there is no field here and we will say that the mean collision time is τ, this is different from the τ we defined in mobility, this is you know in a in a there is no field here per say. So, electrons will collide and mean position time you say tau and the distance that electrons move between two successive collision is l. So, the sort of the mean free path.

Like you know the between two collisions electron will at least move l ok, it is the mean free path we can say it is the mean path, they will go and say if l is say 10 nanometer it means electrons will collide on an average every 10 nanometer. So, I will take a line here and I will draw a box the very infinitesimally thin box here, you know which is at $x_0 + l$, 1 mean free path.

And on the right side I will take a box slightly larger in the other side in height, because of course, you know on left side your concentration is high on the right side your concentration is low so, its gradually increasing. So, this is $x_0 - l$ the distance I am taking two boxes why am I taking two boxes I am taking to in very thin boxes of thickness only l , the mean free path. And I am going to take the electron concentration here. So, this is an electron concentration is varying right electron concentration is varying there.

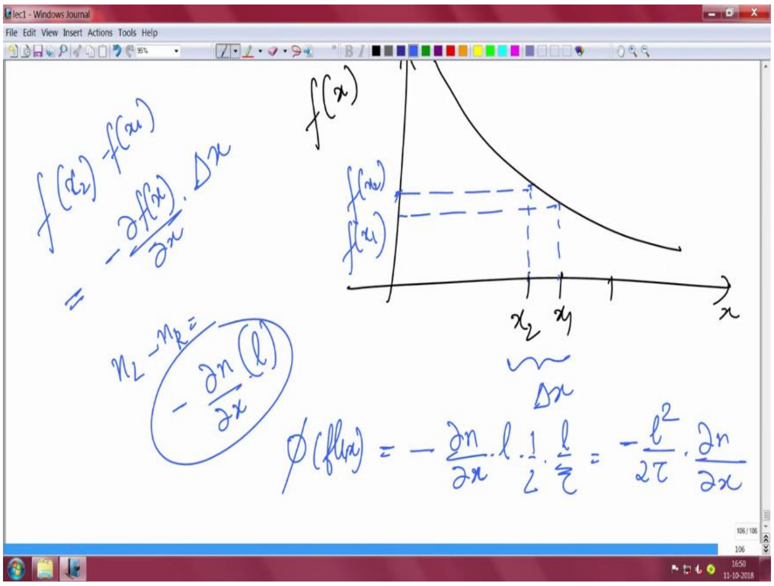
So, suppose this value this value is this is on the right of x, x_0. So, I will say n_R this is the electron concentration. So, suppose this is 10^{18}, this is 10^{17} and so on and so on right. So, this is n_R some value here this is on the right side of x_0, on the left side of x_0 this is suppose n_L left l of course, n_L is greater than n_R because its decreasing function right. Now, at any given point in time the electrons that are there in this box, half of them will move this side half of them will move that side its random. Similarly electrons that are there in this box half of them will move this side half of them will move this side because it is random.

We are interested in considering or finding the flux of electrons that are actually crossing the plane of x_0, this plane of x_0 here what is the fraction what is the flux of carriers crossing x_0 from left to right. So, I told you $n_L/2$ is crossing from left to right you agree a and $n_R/2$ is going from right to left. So, the net that is actually flowing the net that is flowing to the right what is the net concentration or a net you know the flux of electrons that are flowing from left to the right from left to the right is $\left(\frac{n_L - n_R}{2}\right)$, because half of this block are going to right half of this block are going to left so, the difference of that.

So, the net flux of carriers moving across the plane at x_0 will be given by the charge, here I mean the total number of carriers here times the velocity. So, the flux of carriers that are crossing the plane x_0 is given by the total carrier which is $\left(\frac{n_L - n_R}{2}\right) * v$ and velocity is nothing, but distance by time. The mean distance from centroid to centroid is actually l. So, it is l, I told you mean free path by the time it taking which is Ꞇ, Ꞇ is the mean free time you know this the mean collision time. So, in time tau it is going there right. So, now, I can say the, $\emptyset = \left(\frac{n_L - n_R}{2}\right) * (\frac{l}{\tau})$, this is your flux.

Now, if you recall your high school physics you know if you recall your high school physics I have a function f(x) and this is suppose x this is function x you know, if I take 1 point here x_2 and another take say point x_1 very small very close to each other they are infinitesimally close almost, then x then at this point you have $f(x_2)$ at this point you have $f(x_1)$ so, let me right it down in a different slide probably, it is a high school physics high school math actually.

(Refer Slide Time: 29:59)



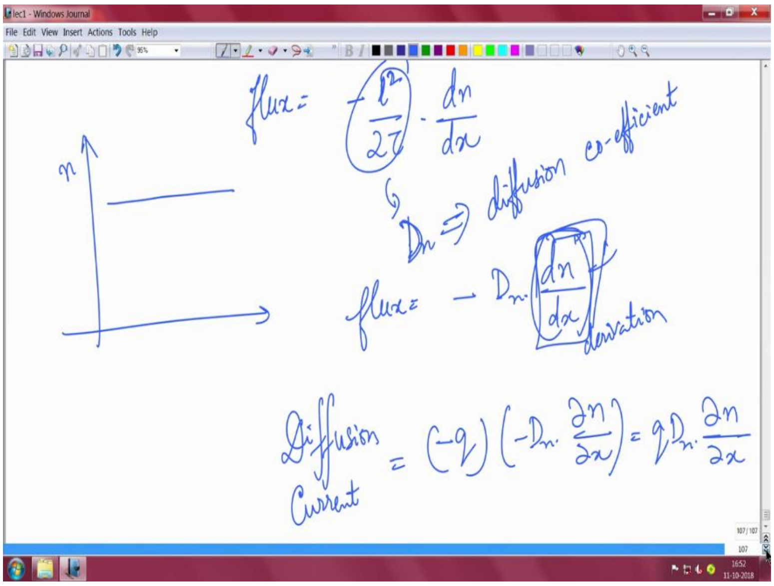
This is f(x) this is x this is say x_2 this is say very close to it x_1 and this is going like that. So, x_2 is this x_1 is this is $f(x_2)$ this is $f(x_1)$.

You notice the similarity between this figure and the figure before, if you notice the similarity between that figure and the figure before, you will see that this is actually n_L which is like $f(x_2)$ and this is like n_R the right box which is like $f(x_1)$. So, remember this function $(n_L – n_R)/2$, this is like excuse me this is like $(f(x_1) – f(x_2))/2$ what it means is that if I take this, then $f(x_2) - f(x_1) = -\frac{\partial f(x)}{\partial x} * \Delta x$, can you write that the slope times this we can write that right.

So, similarly in the previous function n_L if you look into this, if you look into the previous slide here $n_L – n_R$ that can be written as how you know that can be written $n_L – n_R$ can be written as minus d sorry, it can be written as -$\frac{\partial n}{\partial x} * l$, because l was the main delta you know the drift difference. So, let me write down the flux again the flux of carriers moving across the plane, if you remember the flux of carriers moving across the plane here was given by this quantity right this quantity.

So, I will write that quantity as minus now, I will use this $\frac{\partial n}{\partial x} * l$ ok, what was that $\frac{1}{2} * \frac{l}{\tau}$. So, this is $-\frac{l^2}{2\tau} * \frac{dn}{dx}$.

(Refer Slide Time: 32:33)



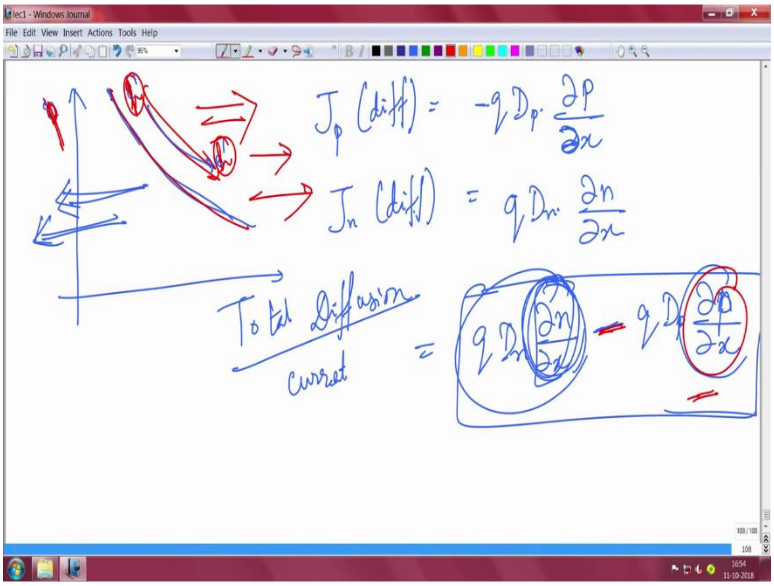
$Flux = -\frac{l^2}{2\tau} * \frac{dn}{dx}$, I can call this quantity as D_n which is diffusion coefficient, it is a coefficient it is a constant depends on temperature depends on temperature, depends on also doping into some extent ok, but more or less I can define it to be D_n and so, I can write the $Flux = -D_n * \frac{dn}{dx}$, done.

So, this is the derivative actually this the derivative of the concentration gradient. So, if your n the electron concentration with gradient is varying like this, this is a definite concentration gradient. So, there is a diffusion if on the other hand if your derivative- there is no gradient like constant, then this quantity will become 0 and so, there will be no diffusion current.

So, diffusion current diffusion current is given by there is a charge of electron is negative right. So, -q * Flux which is $(-D_n * \frac{dn}{dx})$, $Diffusion\ Current = qD_n \frac{\partial n}{\partial x}$, this is the diffusion current. Of course, if this is current density so, if you multiply by area it will become amp otherwise it will become amp/cm^2.

Similarly for holes you can define the diffusion current and because the charge of hole is positive right, the charge of hole is positive your hole diffusion current.

(Refer Slide Time: 34:05)



I will call it $J_p(diff) = -qD_p\frac{\partial p}{\partial x}$, the slope will decide of course, slope will decide and your electron concentration of diffusion current, $J_n(diff) = qD_n\frac{\partial n}{\partial x}$. So, the total diffusion current if both electrons and holes are present, if both electrons and holes are present and both of them are diffusing then the total diffusion current will be given by $Total\ Diffusion\ current = qD_n\frac{\partial n}{\partial x} - qD_p\frac{\partial p}{\partial x}$. This is the total diffusion current if both electrons and holes are going to diffuse.

Remember this sign and this sign is important, because you have to also considered a slope this of slope of this and this for example, if you have n going like this then electrons you know certainly will diffuse from here to here and so, the current will flow in this direction because electrons direction is opposite to current direction right. And that you can capture here you see your this slope $\frac{\partial n}{\partial x}$ will be negative because its coming like this.

So, negative slope if you put here its negative this quantity will become negative and that is indicated by this the current the total current. On the other hand your if you have holes here p and the holes will then diffuse also from here to here, because higher concentration of hole to lower concentration of hole, but hole direction is the same as the electricity direction. So, current will flow in this direction.

So, in this case the hole slope is also negative here if you put a negative term here, then this negative that negative will cancel out. So, it will become positive which means this is the positive x direction in which the current will flow. So, we shall wind up the lecture here today we have introduced diffusion current diffusion of electrons and diffusion of holes. And we derived the expression for the diffusion current in terms of the derivative of the concentration gradient introduce both the hole and the electron concept and also before that we have also discussed on the velocity saturation, temperature dependence of electron mobility hole mobility is similar trend right.

So, now we know drift and diffusion. So, now, we can actually go ahead and discuss about current flow. These are actually current equations by the way now we will discuss certain relation between drift diffusion and we are ready to now understand devices, but before that the slight few more things we will have to discuss.

So, we will take up many of these things in the next class including the relation between drift and diffusion for example, and also how a high drift current means a high diffusion current also without those things, there is something called Einstein relation we will come to their Einstein relation and from there we will take on a few other things before we can touch on the devices. So, we will end up the class here.

Thank you for your time and we will again meet on the next class.