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

Lecture – 10
Carrier scattering and mobility

Welcome back. So, we ended the last lecture with this promise that today we shall start mobility. We are we should not forget what we have learnt till now about doping and carrier concentration and how to calculate carrier distributions and so on. We will go ahead and study mobility today and once the word mobility basically means that we are now in the discussion of low field you know transport way. So, what is this low field transport high field transport. Those are the two things we have to at least get to be aware of the names you know what is meaning of the name low field and high field transport is.

What is mobility and why it is important in current flow, why is important in carrier transporting and is electron mobility a fundamental quality. And, what about hole mobility and how will mobility affect device performance if I take about LED or if I talk about a transistor, are actually mobility of carriers like electrons and holes important. Those are the things that we have to understand in the light of practical devices also as we discussed we only not only discuss the mathematics and physics, but we have to also calibrate ourselves as to what we are learning and how are they important for the practical day today devices ok.

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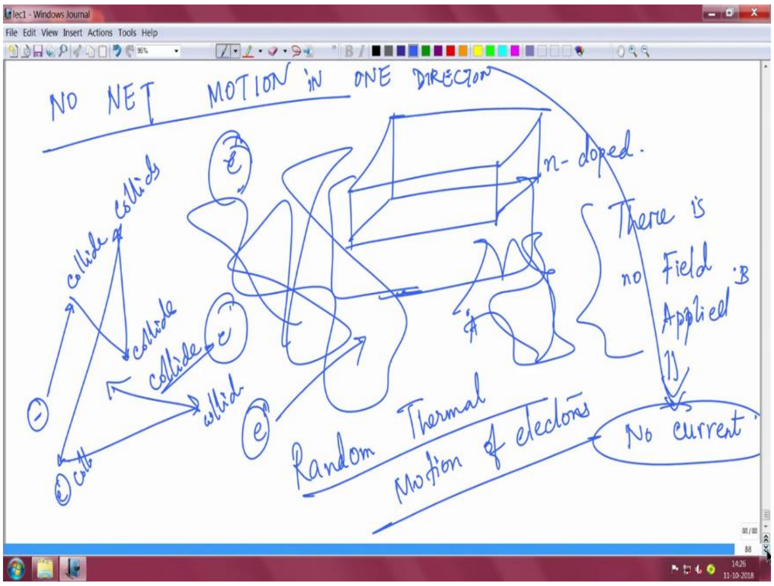

So, let us come to the discussion of mobility today. If you talk of an electron for example, and you are talking about a sample for example, suppose you have a piece of silicon block for example, you know there is a silicon block here and there are electrons here suppose this is n type doped silicon ok. So, there are electrons here. These electrons, if you do not know the applied fields, suppose there is no field, you are applying no field no electric field is applied. If there is no electric field applied, then it is uniformly n typed dope right.

Even if you connect a circuit take a wire there is no field applied no voltage is applied there is no field means there is no voltage. Then there will be no current also because you know it is in equilibrium. So, electron will collide with many other things, what are the things it will collide, electron will have a random thermal movement at any temperature right. See I am talking about room temperature there will be a random thermal motion of electrons, there will be a random thermal motion of electrons and this is without any application of field.

So, electrons will move randomly suppose they have an electron here it will try to move that will collide with something and then again it will move, it will collide with something keep moving then again collide random direction completely random. Maybe it will move here again it will collide and move here collide this a collision here then move here collide ok. What will happen- there will be no net motion, everything is random motion, everything is random motion. So, it will keep moving zig zag zig zag zig zag zig, but it will not eventually moved to another means there is no net motion of electrons from one place to another its basically coming back to the same position eventually after lock large number of collision ok.

It is colliding and then it is coming back to its own position its randomly colliding. So, an electron that is at point A will never reach like a point B here it will basically keep colliding, colliding, colliding. There is no random motion this all random motion because of thermal vibration and because of this random motion there is no net movement of the electron in one direction. There is no net movement of electron in one direction and because there is no net movement in one direction there is no current.

Current will only come when there is a movement of electron in one direction coherently you know, I mean not coherently you know at together there should be a total movement of electrons in one direction, if it is not moving then there is no current. So, this in a random thermal you know vibration and this is happening without any application of field it is just a random sample. And what are these collisions taking place from you know and I say an electron is here it is colliding, is colliding and its changing the direction again is colliding here again changing the direction.

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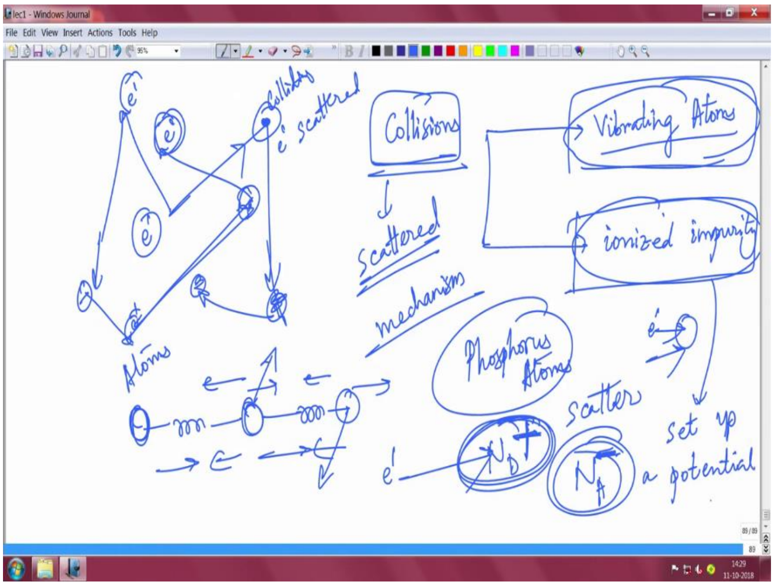

So, these collisions these are not electron-electron collisions for a moderately doped semiconductor electrons electrons do not collide electrons are I mean subatomic particles wave particle right. Collisions actually happen with two things; one is that electrons will collide with vibrating atoms. In a crystal, in a silicon semiconductor, for example, the atoms will be vibrating at room at any temperature they will be vibrating except 0 Kelvin they will always be vibrating; more the temperature more will they vibrate. So, they are vibrating strongly at room temperature, if you raise the temperature to 50 or 100 degree Celsius they will vibrate even more. So, the atoms keep vibrating.

Because you see you can think of atoms these are atoms not electrons. You can think of atoms like they connected by spring; they connected by spring and they are actually vibrating, they keep vibrating. There are different modes of vibration like they might vibrate you know to they might come close together, they might go away from each other out of phase, they might one may vibrate this side one may vibrate this side; so, there are different modes of vibration. These vibration of the atoms can you know scatter electron. When the electrons collide we call that they are scattering electrons are getting scattered from this collision ok.

So, these are collisions are happening, but actually electrons are getting scattered right. So, this vibrating atoms can scatter electrons ok. And secondly, ionized impurity also can scatter electron, ionized impurity where is ionize impurity coming from are they that phosphorus atoms that you have put know; the phosphorus atoms that you have put to dope the semiconductor after giving the electrons away what remains is N_D^+ I have told you. What remains is ionized donors or if you are adding boron for p type what will remain will negatively charged ionized accepters.

So, this ionized donors and ionized acceptors when ionized positively ionized donors and negatively ionized accepters, these ionized donors will also scatter your electrons or holes. So, this electrons and holes that are scattering here if it is n type it is electron only you know they are scattering then colliding here then going here, then going here and going here there is no net movement there is no net motion no current flow. This collisions each of these collision can happen either because, of vibrating atoms or because of ionized impurity either of these two primarily there maybe other also.

But, these are the two primary scattering mechanisms you can say scattering mechanisms or they are the collision mechanisms that will you know the reasons why the electrons will collide and basically keep coming back to the same place of the large number of collisions is all random. And when I say, the vibrating atoms actually are colliding or scattering it is not like the electron directly comes and hits atom or even you know when I say it is a negatively charged accepter positively charged donor, it is not like the electron comes and hits it physically. There is no physical hitting here. What is happening actually is that, this vibrating atoms or this ionized impurities they setup a potential, they set up a potential energy and that potential energy perturbs the electrons motion.

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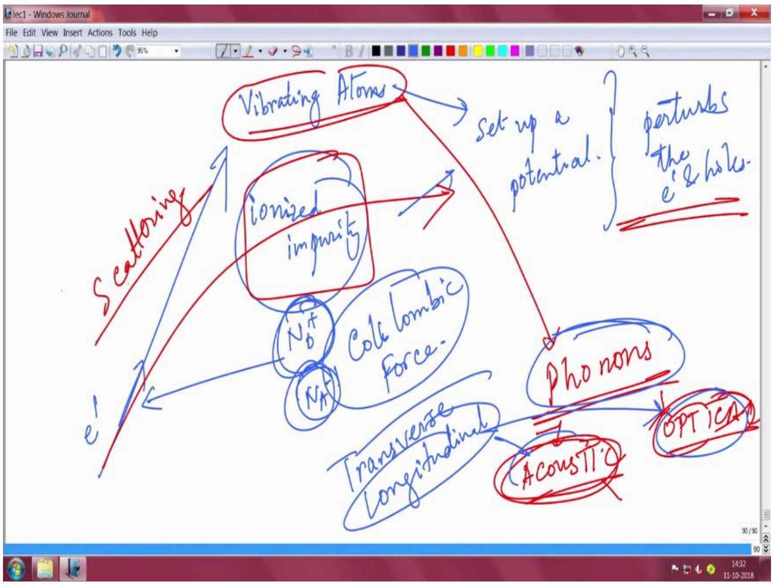

This actually this vibrating atoms, the vibrating atoms or ionized impurity they basically set up a potential, set up a potential energy because of their vibration or their charge and so on. And, this potential actually perturbs or scatters the electrons and holes whatever as it right. So, this is actually a for example, ionizing impurity scattering when you have N_D^+, it will have a Coulombic you know attraction or repulsion Coulombic force it will attract or repel an electron, in an electron that is going will be attracted you know by Coulombic force of it is N_A^- it will be repel by the Coulombic force.

So, the electron is going this way. Suppose this ionized impurity will because of the Coulombic force the electrons path will be changed like this and that is scattering that is scattering that is scattering and it is a perturbation that has been set up it actually needs complicated quantum mechanics to try to solve this equations and do, which we are not doing in this course.

But this vibrating atoms and ionized impurities they set up a potential field and you know that potential basically perturbs the electrons motion or holes motion and thats what they scattered by the way this vibrating atoms you know this vibrating atoms have a word we call them phonons. A phonon is a unit of vibrating atom we call them phonon; when I say phonon it means that the atoms that are vibrating we call them collectively phonon. It has many types, but primarily there is one acoustic phonon you know acoustic phonon and then there is one optical phonon and each of these acoustic and optical type of phonon why are we calling them acoustic and optical they depend on the way they are vibrating.

They might vibrate out of phase, they may vibrate in phase and so on. So, there are ways to decide that. So, there is acoustic and optical mode they both have one transverse mode and one longitudinal mode of vibration transverse and longitudinal. So, there is a transverse mode there is a longitudinal mode for each of acoustic and each of optical phonon that there is this ways they have vibrating actually is what defines them. Anyways we will now have to go to acoustic and optical in this course we can just collectively call them phonon or vibrating atoms they scattered the electrons and Coulombic force of the impurities also scattered electrons and that is why electrons you know do not eventually move from one place to another collectively they are just randomly moving around scattering. You know they are not actually not getting any current right.

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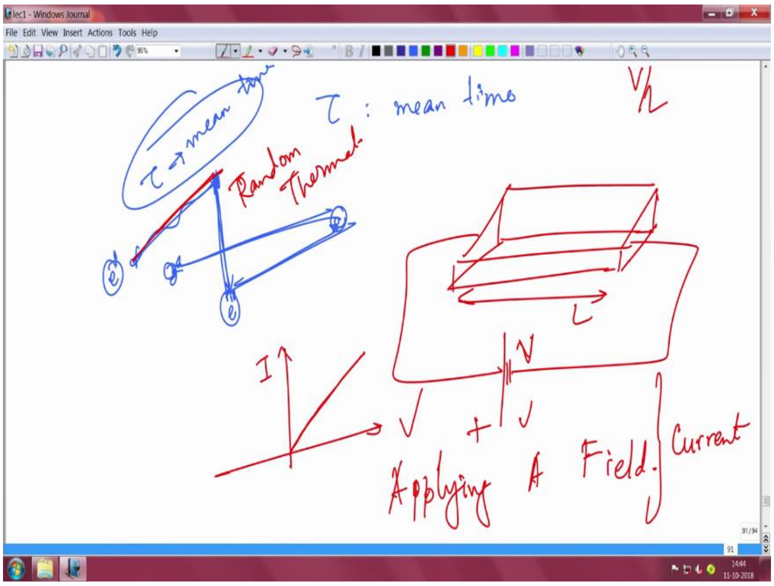

So, I can say is the mean time between two successive scattering; so, between two successive scattering. So, I have an electron that is here it scatters somehow its gets a collision moves h‘τ’ ere and then again it scatters moves here again it scatters moves here.

So, the mean time the mean time between two collision the mean time between one collision and other I can call it ‘τ’. You know there will be many ‘τ’(taus) here τ_1, τ_2, τ_3 and then mean will be ‘τ’ the average time that is taking within collision we will be called ‘τ’ that is all good.

Now, suppose you look at this you know the semiconductor I had given you know this example, that there is a semiconductor that silicon semiconductor for example, this is a silicon piece of silicon. Now what if I apply a field there; what if I apply a field there. Suppose I have a piece of silicon I will just draw just a block maybe like this right. So, I have a piece of silicon here ok. Suppose I apply a voltage now which means I am applying a field applying a field what will happen then?

Then there will be current if I apply a field then there will be current what is happening then it means this a thermal initially this is random thermal you know the random thermal vibration or random thermal motion that was happening that was not carrying any current. But now there will be current. What is happening is that the moment you apply a field what will happen is that there will still be collisions. So, electron is here.

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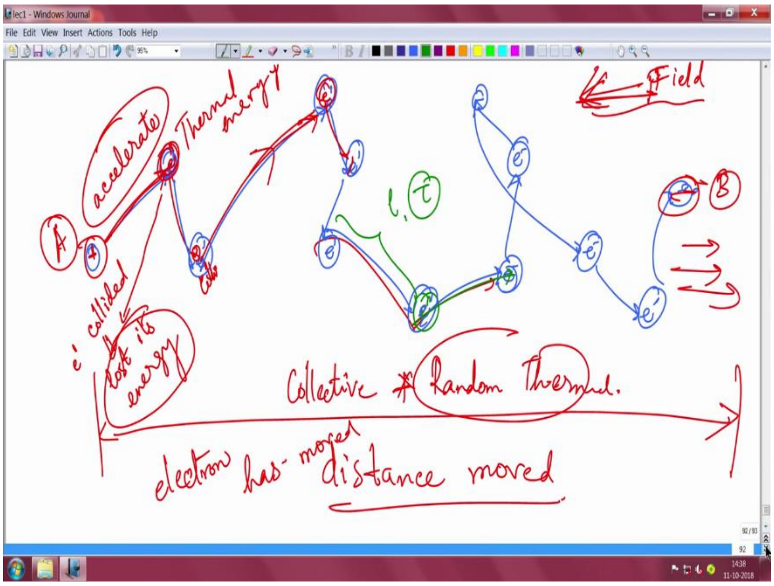

Suppose it scatters. Suppose it scatters again scatters, scatters, scatters, scatters keeps scattering it keeps scattering, but over the finite period of time the electron has moved this distance the electron the electron actually has moved this distance over time has moved this distance right. Electron has started with point B A it has reached a finite point B in some time d it actually has gone from here to here it has gone.

Of course is not gone in a straight line which has gone in many collisions maybe hundreds of collisions, but there is a collective motion of electron now. Although there is this random you know there is a random thermal collision keeps happening random thermal collisions are keeping happening, but electrons are actually moving now in one direction. So, we can get current electrons are moving what is happening here is that although there are random thermal collisions that are happening, but because there is a field the field is in this direction, the field is in this direction thats why the electrons are moving in the opposite direction.

The field is in this direction, the field will accelerate the electron from this point to this point ok, field will accelerate the field will accelerate, but it will collide with a phonon or it with a ionized impurity it will collide the electrons will collide here right. So, electron has collided, the moment it has collided with a phonon of vibrating atom or an impure ionized impurity the electron has lost its energy lost its energy that is gained from the field. See the moment electron accelerates its basically is gaining energy right force and the moment it is you know accelerating is gaining energy the moment if its colliding with something else its losing its energy that it has gained through its acceleration from the field.

Remember these all happens because of there is a field you know. It loses when it comes back to its random thermal energy, the thermal energy it again it has, but again the field is accelerating. So, again it will go right it will again go again it will lose the energy of collision here, again it will come back to thermal state again the field will accelerate right it will gain energy, but again it will collide it will lose again (Refer Time: 14:48) its keep going on. So, this acceleration losing energy and collision acceleration loosing energy and collision.

This process will keep going on electron collectively keeps moving forward and forward and forward. So, there is a net motion of electrons in this direction there is current flow this is your electron transport that is happening you know and as long as you are increasing the field your electrons will keep moving faster that is called your low field transport beyond the certain point you cannot keep increasing the field indefinitely because after sometime the electron speed will get saturated and that we call a high field transport we will come to that quickly right. So, here we have to define the concept of mobility.

So, what is happening here is that if I again come back to this slide what is happening here is you know where is the green colour is yeah what happening is that the average distance it is travelling I can call it some you know some L, "L" is the average distance that the electrons are covering before they are getting collided and 'τ' is the average time it takes for collision to happen right. And as I told you at each collision basically the electron loses the energy which has gained from the field comes back again to the thermal energy kind of a state its has the thermal motion again it gets accelerated and keeps going forward right.

That's happening what is happening. So, if I look carefully the current we will come to the current little later.

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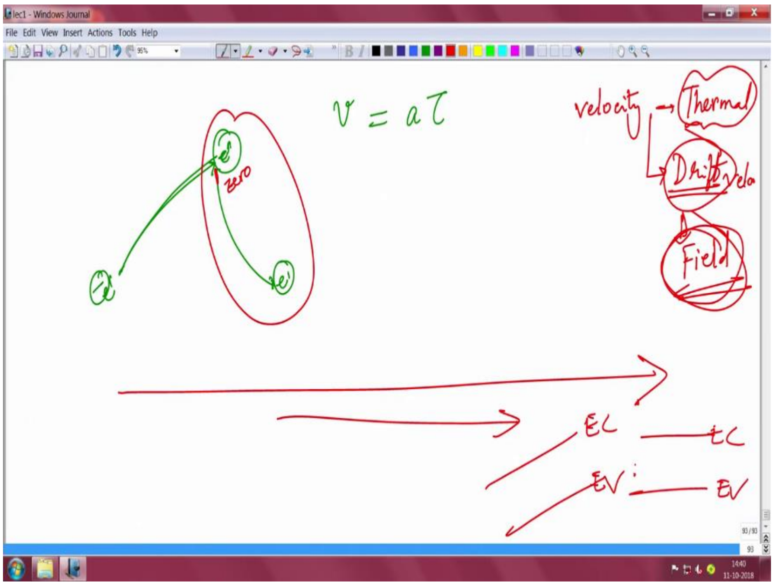

I will come about you know the velocity if I start from 0 the velocity is given by acceleration times the time. So, you know electron is here it is getting scattered up to here and its accelerated here again it loses the energy and comes back here. So, if I take these for example, so, if I take this segment it will start from 0 the velocity will be 0 because there will be a thermal velocity, but thermal velocity is random what is moving the electron from one point to another point here is the field electric field.

The thermal velocity will be random field will give a definitive directed velocity ok. The field will allow the electrons to it will have a direction, directional definitive velocity because thermal velocity is random it can be in any arbitrary direction, but here the electrons will move in one direction right. So, the velocity of electron has two component one arises because of thermal which is random and this thermal random motion will not contribute to current. Because, it will be in all kinds of direction it's not contributing to current then there is another component of velocity in the presence of an electric field only and we called it the drift velocity.

The word drift the word drift means that current is flowing or electrons are moving or whatever happening in the presence of field. If there is no electric field, drift will not take place this remember this electric field need not be externally applied sometimes the electric field may exist inside a semiconductor even without the application of field. I told you if there is a slope in the conduction of valence band it means there is a field. Instead of the conduction band being like that and valence band being like that, if the conduction band is like that and valence band is like that there is a slope here it means there is a field.

That field need not be applied externally. So, the whenever there is a field whether external or internal there will be drift whether that drift is eventually leading to current is different because it might be opposed by diffusion that is another thing, but drift component will exist when there is a field.

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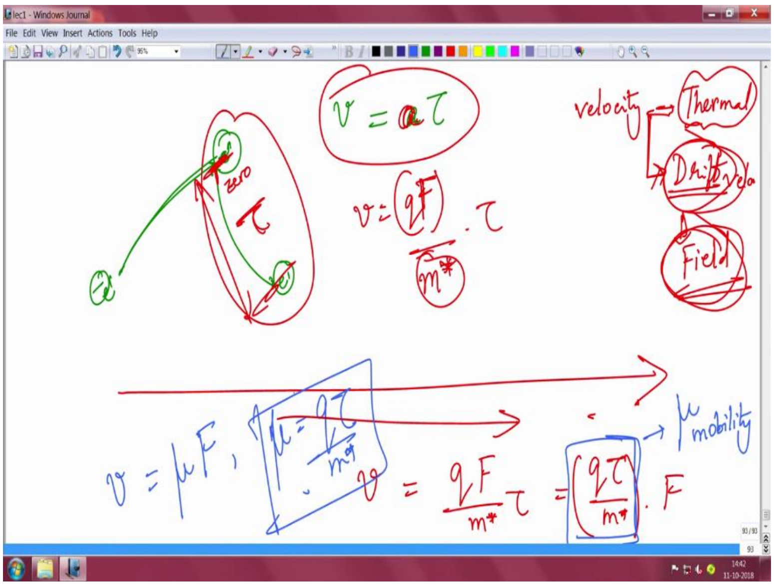

So, velocity has a thermal velocity that always exists. You know because of the thermal motion then there is a drift velocity which arises because of the field that we are applying. So I am talking about the drift velocity here the acceleration that is you know the field is giving an acceleration times the time it takes from this point to this point. This is the distance you know:

what is the velocity.? The acceleration times the time which is taken you know that is what is happening.

What is acceleration? Acceleration is nothing but, force times force divided by mass. Force is nothing, but charge times the field you applying this is your force the charge times the field is actually your force divided by mass.

And here you have to use the effective mass I told you effective mass basically takes into account all the quantum mechanics in the material right into ‘τ’. This ‘f’ is the field you applying. So, I can write velocity (v) = q* F, which is the force divided by the mass times the average time. So, I can write it as (qτ)/m* same thing into field. This quantity I use the ‘μ’ and I call it mobility this time .

So, I can write v = μ*F where, mobility is equal to (qτ)/m* .

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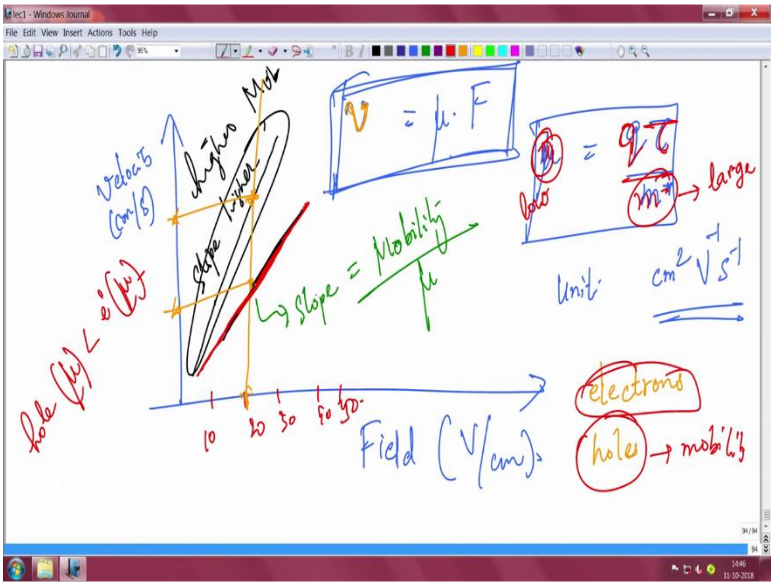

The units of mobility μ= cm^2/V-s. So, you see velocity and field they are linearly proportional, and the slope is called mobility. So, if I plot velocity of a particle centimetre per second on the y axis on the x axis I am plotting electric field. So, this is volt/cm electric field then, the velocity will keep increasing linearly with field, the velocity will keep increasing linearly with field. What does it mean ?

Physically it means that as I am increasing the field more and more suppose it is 10, 20, 30, 40, 50 you know I am increasing the field.

And if I am increasing the applied electric field then the electron is moving with higher and higher velocity electron is becoming faster and faster which makes perfect sense. The more force you applied faster a particle will go, so the more electric field I am applying more will the you know the faster the electrons will flow and which means at higher field actually means the higher voltage I am applying across the same distance right.

So, if I am applying a voltage v, if this distance is L then field is generally v/L right. So, if I keep increasing the voltage, I actually keep increasing the field. So, if I keep increasing the voltage the electrons will move faster and faster and because the electrons move faster the current also will increase and that is why, if I plot I versus v it will keep increasing. Because electrons are increasing their speed that is why current is increasing with voltage which is actually a way of saying that electron speed is increasing with respect to field and as you might now realise the slope of this velocity and field is called mobility.

So, the mobility of electrons actually is a indication of the slope between velocity and field. It indicates how rapidly you can change the velocity by applying a field. If we have this is one for example, this is one material, this is one semiconductor say ‘x’ another semiconductor ‘y’ has a velocity field like this suppose this is the curve. Now, this slope is higher no- this slope is higher than this slope which means that this particular material which has a characteristic like that has a higher slope which means it as a higher mobility it has a higher mobility.

What it means is that for the same field for the same field I can get a higher velocity in one material than the other material. For the same field I can get a higher velocity in one material than the other material that is what it means the slope. So, mobility is very essential and it is the slope that will come up here and remember this velocity is drift velocity it comes here it comes into picture when you apply a field ok. So, the moment you apply a field this will come into picture. So, this is all about this is at the starting point of mobility actually and different materials will have different mobility. Electrons will have their own mobility and holes will have also their own mobility right holes also will have their own mobility.

Now, if you look mobility is charge which is say constant, times mean scattering time/m. If the effective mass is large, then your mobility is low. Holes typically have larger effective mass than electron which means hole mobility is lower than electron mobility your hole mobility is always lower typically almost always lower than electron mobility. That is why holes are slow if you make a device based on holes it will not be a fast device so much.

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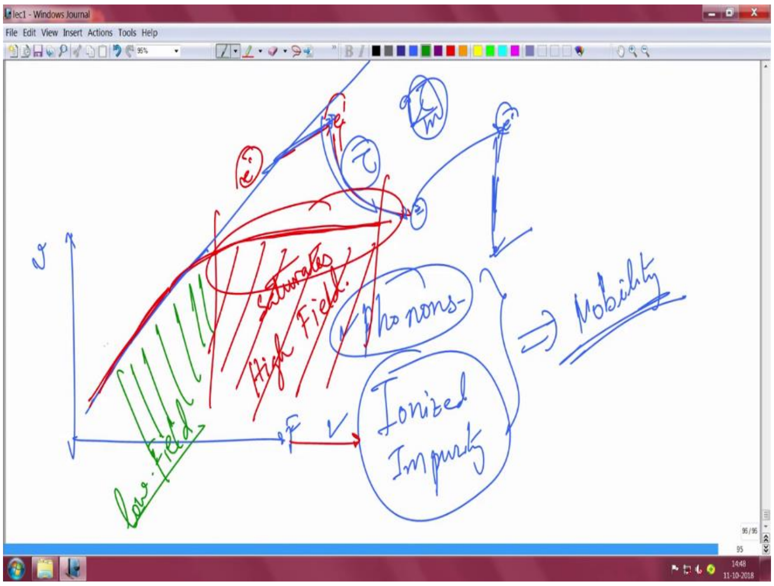

Now, I told you that electrons scatter and collide right they will scatter and collide sorry they will keeps scattering and colliding like that, like that right. They will keep colliding and scattering and this is because of either phonons or ionized impurity I told you that right. So, phonons and ionized impurity will have an effect on electron or in a hole well talk about electron only mobility. The more they scattered the more they scattered the lower will be the mobility, which means the more frequency the electrons will scatter if you which means if you are scatter more frequently your ‘τ’ will come down. The mean free time that are spending between collision will come down, if it comes down in (q*τ)/m this also comes down. So, your mobility also decreases. So, more frequent collision leads to lower mobility and phonons and ionized impurities will scatter electron.

They scattered electron little differently, they have a different temperature dependence with respect to mobility and also, they also have dependence on may be no dependence on the carrier concentration that you have. So, there quite few things that you have to talk about and also if you remember you know velocity, and this is field. I told you the slope is the mobility, but this cannot keep increasing otherwise it will exceed the speed of light one line you know that is not possible.

So, after some time actually it will saturate this velocity will saturate. Once the velocity saturates then mobility no longer plays a role. This is called high field transport. In high field transport, we have velocity which was linearly increasing at the field will not saturate which means even if we increase the field the velocity will not increase it will saturate. So now, the slope has become 0 you can say the mobility does not play a role now. This is actually called the high field region when the velocity has saturated right and this is called the low field region, when your velocity and field are linearly proportional this is the low field and it will enter the high field. They are many devices transistors that will operate in the low field region sorry and then many transistors that will operate in the high field region. So, those are all things that you must keep in mind as we go ahead right.

So, this how electrons are scattered by phonons and how electrons or holes are scattered by ionized impurity is very important because, that will tell you how mobility will change, and this is a very important concept that you have to understand. So, in the next class we will take this up. So, we will wrap up the class here. So, phonons and ionized impurities how are these two things affecting the mobility of carriers. And, how are they are dependence on temperature for example, if I heat a substrate or sample if I increase the temperature from say room temperature to 100 degree Celsius or if I cool it down to say minus 100 degree Celsius.

How will phonons scattering or vibrations atomic vibration scattering and ionized impurity scattering. How will they affect the electron mobility? This is extremely important because mobility is very sensitive to all this things and electron mobility will define how much current will eventually flow and how much current will flow will actually determine how that device is performing. So, that is why if you can you cannot take a cell phone to very high or very low temperature even before you know intrinsic condition sets in your mobility will go crazy, your mobility will increase or decrease a lot when you take your cell phone to a higher lower temperature.

Because, there transistors in your processors and memory you know all this chips that are there and once your mobility of fundamental material silicon for example, it changes with temperature then the current that will flow in the chips will also change and if that changes then all your logic CMOS everything that is there will go for a toss. That is why it is very important that we understand how mobility changes, as a design engineer you have to take into account how mobility changes with temperature, or with impurity background concentration.

So, that your device design is realistic you can say that this iPhone will operate only between 10 degree Celsius to say 50 degree Celsius, there is always a range there right. So, there many things that come into that. So, from the next class we will take in the understanding how temperature dependence on a what kind of temperature dependence phonon and ionized impurity scattering has ok. So, I will end up the class here.

Thank you for your time.