Semiconductor Device Modeling
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Lecture-07
Semi-classical Bulk Transport: Qualitative Model

In the previous lecture we talked about the balances of carrier density. Momentum density and energy density. These parameters related to the carriers. We talked about the balances under equilibrium conditions. We explained what each balance means. Then we said that we disturbed the Equilibrium to create a directed motion this directed motion we analyzed under 2 situations namely quasi-equilibrium and non-equilibrium.

So when the disturbance from equilibrium is small we explained what are the balances in carrier momentum and energy then when the disturbance is large non-equilibrium conditions for that situation also we explained what are the balances in carrier momentum and energy how in terms of balances of these 3 quantities. Which is analogs to talking about physical phenomena in terms of mass conservation momentum concentration and energy concentration.

How in terms of these we can explain the linear relation between velocity and driving force for small driving forces and such addition of the velocity for large driving forces then we introduce the concept of carrier temperature. So we said that the random thermal energy of carriers the random energy off carriers even under applied voltage. Which includes the thermal energy as well as energy acquired from the electric field.

So this random component the random component of this energy. Kinetic energy of carriers can be associated with it temperature called the carrier temperature in the same way as we Associate lattice temperature with the random vibrational energy of lattice items or are we associate an ambient temperature with the energy density in the ambient We also explained with an analogy. How the balances between.

The energy of the carriers and energy of the phonons is achieved how the energy exchange happens between them. How the energy of the carriers can be much different from energy of the phonons or the temperature of the carriers can be very different from temperature of the phonons. Now. We want to proceed from this point and explain. Some of the other phenomena such as velocity overshoot.

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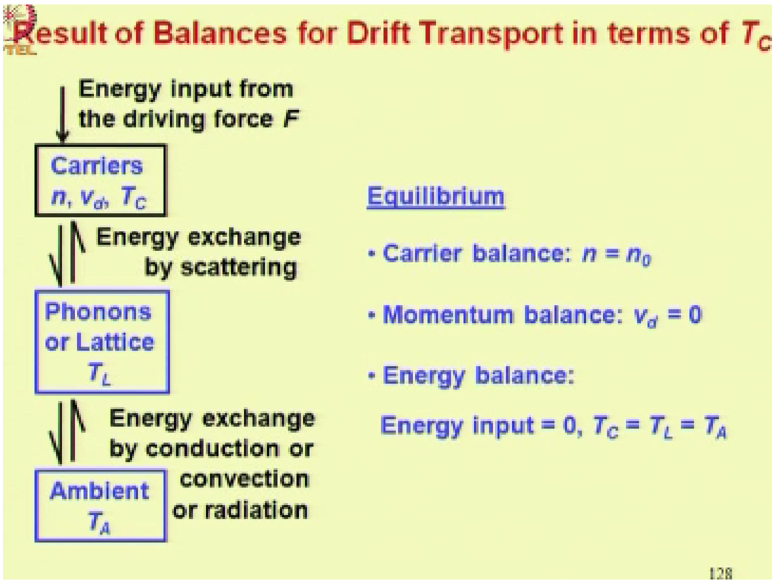

So here is the reputation of. Some information related to carrier temperature from the earlier lecture. Where we talk about the carriers the phonons and the ambient and the energy exchange between these entities the energy input from the driving forces is directly into the carriers so it is a carriers which derived the energy out of the forces and then by energy exchange through scattering.

They pass on the energy to phonons and which in turn pass on the energy through phenomenon of conduction, convection or radiation to the ambient. Let us. Talk about the result of balances for drift transport in terms of the carrier temperature. So here this means we will discuss about what happens to the carrier concentration and the directed velocity VD or drift velocity VD.

And carrier temperature under equilibrium carrier balance results in the relation carrier concentration n0 equilibrium carrier concentration momentum balance leads to the conclusion that drift velocity is 0. And energy balance leads to the conclusion that the carrier temperature is = lattice temperature = ambient temperature here. Energy input in this case is 0.

Let us move to Quasi-equilibrium. In Quasi-equilibrium the carrier balance is the same n = n0, result is the same for carrier a balance for momentum balance. You get a drift velocity which is approximately = force into the momentum relaxation time under equilibrium. So there is a momentum divided by the effective mass so between 2 collisions this is the drift velocity that a carrier acquires.

The momentum relaxation time is approximately equal to that under equilibrium under Quasi-Equilibrium. This is drift velocity which is > 0. However, it is much less than it thermal velocity, that is the meaning of. That drift velocity is much less than thermal velocity. Because we explained earlier that the saturation the velocity is of the order of the thermal velocity.

The force on the carrier is given by - q times electricity for drift transport now the energy balance what the energy balance says is that the energy input is small from the driving force this energy is small. The carrier temperature is approximately equal to lattice temperature so this is the statement of quasi equilibrium. That the energy. Of the carriers and phonons is more or less same the difference is not much even though the carriers are getting energy from the driving force.

Because that energy gained is small however both these temperatures can be different from the ambient temperature okay, so these temperatures can be more now this is because.

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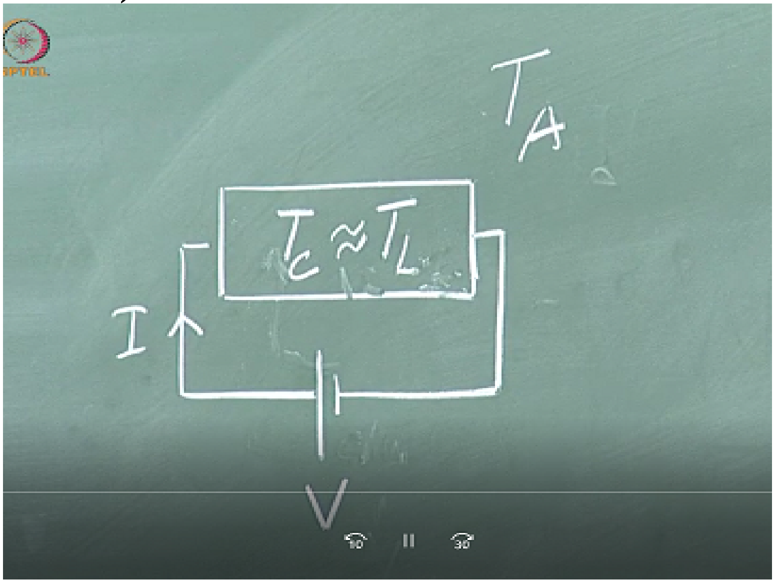

Suppose, we consider a simple block and you apply voltage here, A current flow is set up I and this is voltage V. Now I into V is the power input into the sample now this power is going to be disappeared as heat so when the semiconductor dissipates heat its temperature. Can be different from the temperature of the ambient now inside we have separated the temperatures of the carrier and the lattice. Okay.

So these 2 however can be same but both of these can be different from TA. Because the register is dissipating energy okay heat so one should not think that under equilibrium the ambient temperature also has to. In quasi equilibrium the ambient temperature has to be equal to the lattice temperature or carrier temperature right that may not be necessary.

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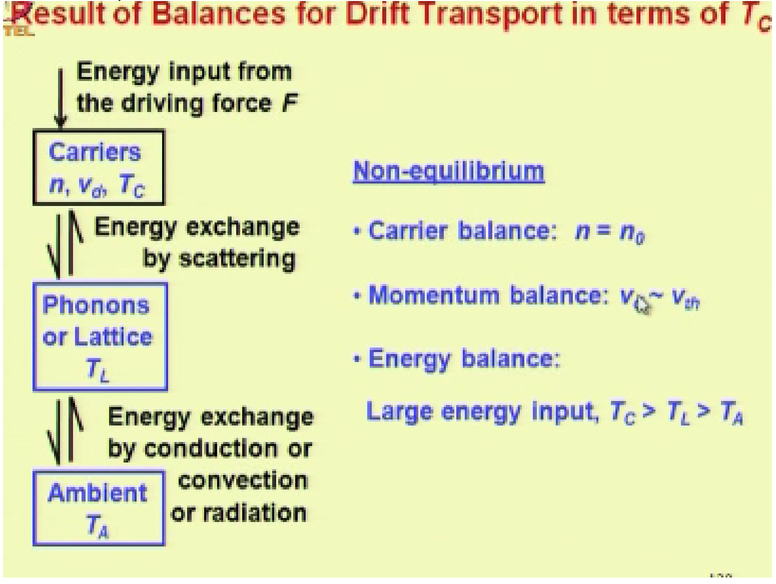

Now let us move to non-equilibrium for the force conditions considered here we do not have any impact and so on therefore the carrier balance. Is leads to the conclusion that the carry concentration is equal to equilibrium carrier concentration the momentum balance leads you to the result that drift velocity gets saturated at about thermal velocity so you see in this equation the force is not there. This clearly indicates saturation okay with the applied force.

The energy balance it says that the energy input is large. From the driving force you are inputting a large amount of energy into the carriers as a consequence the carrier temperature is more than lattice temperature you see this is the situation in non-equilibrium and the lattice temperature is more than ambient temperature because the device or the semiconductor is dissipating heat so now you have a net flow of energy.

From the carriers to the phonons or lattice. And from the phonons to the ambient because the temperatures of these 3 entities are different so you see this is how. The concept of carrier temperature allows you to express the results of energy balance in a very simple form.

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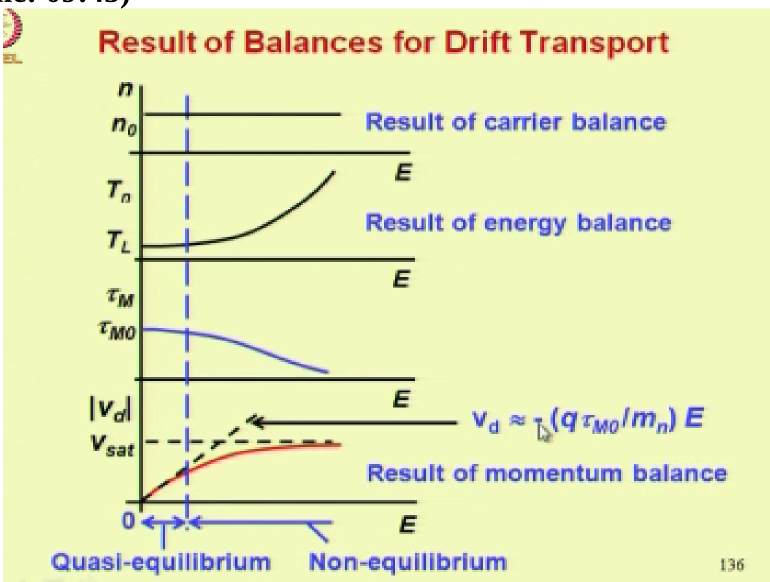

Okay Let us summarize the results of balances for drift transport in graphical form so whatever we have discussed let us it in the form of a graph because a graph expresses a lot of detail in a very compact form so what you can say in many words you can say succinctly in the form of graphs Another advantage of using graphs. To explain your understanding. Is because the graphical graphs or diagrams they mean longer in memory than words.

So the result of carrier balance, n equal n0 as a function of E so E is the electric field that is driving the current in drift. Then let us discuss the energy balance the result of energy balance is that electron energy, kinetic energy of electrons. It remains WN0 when electric field is 0 so here the electric field is 0 at this point. It is WN0, now over a small region here it remains approximately at WN0 because this is Quasi-equilibrium.

So this dash line to the left of this dash line we have dash vertical line blue we have quasi equilibrium. So in Quasi-equilibrium Wn remains approximately = Wn0 and thereafter However, as you enter non-equilibrium region. The Wn starts increasing rapidly with electric field now you can express the same result in terms of temperature if you did that then this is the electron temperature T. Suffix N so we use. The suffix e if you are talking off carrier in general.

To imply either electron or hole but if you are specifically referring to electrons then we will call it a T suffix N. If it is holes that we are referring to then we call it T suffix P. So the electron temperature TN. Remains approximately equal to the lattice temperature in equilibrium and Quasi-equilibrium and thereafter it increases. The momentum relaxation time which is a function of carrier temperature. Or kinetic energy of carriers it changes as shown.

So as the energy of the carriers increases our current temperature increases the momentum relaxation time falls. However, in Quasi-equilibrium it remains approximately equal to the equilibrium value and the fall in the momentum relaxation time occurs in non-equilibrium situation in fact. Quantum Mechanical analysis shows that for large electric fields in this region the momentum Relaxation time is inversely proportional to the electric field.

And that is why the product of the electric field and momentum relaxation time becomes a constant and that is what results in velocity saturation. So here is the velocity which is the result of momentum balance so it increases linearly in Quasi-equilibrium and tends to saturate So this is how from Carrier balance, energy balance and momentum balance we derive the velocity field curve for drift transport.

We will do similar exercise for drift velocity overshoot curves also. Now this straight line here region has a relation drift velocity is given by - Q few time term O/MN into the electric field the negative sign is because. For electrons the velocity is in the direction opposite to that of there is right here and we applauded modules of VD so that it can show things in the positive axis now this quantity Q times term M0 by M.N. Is referred to as mobility about which we will discuss later.

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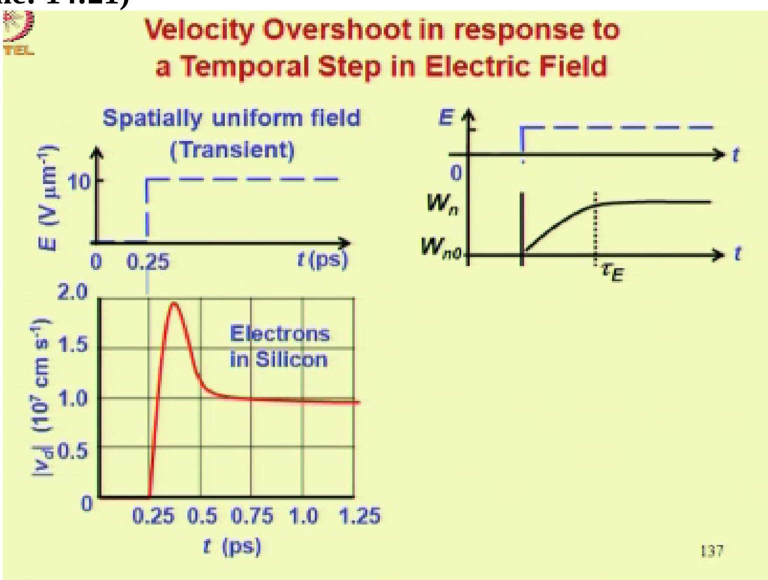

Let us move to velocity overshoot. Now. You will recall that we discussed 2 types of velocity overshoot are in fact 3 types okay, so in one form of velocity overshoot. The velocity overshoot results from the sudden step in the electric field as a function of time the second form of velocity overshoot results from a sudden step in electric field at particular location in the sample but under certain state conditions now these other 2 things 2 forms of overshoot that.

We are going to explain there is a third form of velocity overshoot that is in the velocity versus electric field curve for gallium arsenide. You have velocity overshoot and a negative distance region, now that part will not discuss in much detail in fact I will leave it as an assignment to you. To. Arrive at some simple explanation for this phenomenon so like now let us concentrate on the temporal velocity overshoot which is response.

Which is a result of a temporal step an electric field temporal step means a step as a function of time so this is the result that we have reproduced from earlier slide so the electric field changes suddenly at this instant of time and we assume that the step is sufficiently large so the order of magnitude here is 10 volts per Micron and this is the velocity curve as a function of time and this is what we want to explain why it goes up then comes down and saturates.

The order of magnitude of the velocities are shown here there are the order of thermal velocity room temperature. Also note the duration of the transit here. So you can see it is about 0.3 Pico seconds. Before going on to explain this velocity overshoot let us draw a diagram of the structure and the biasing arrangement in which this is observed.

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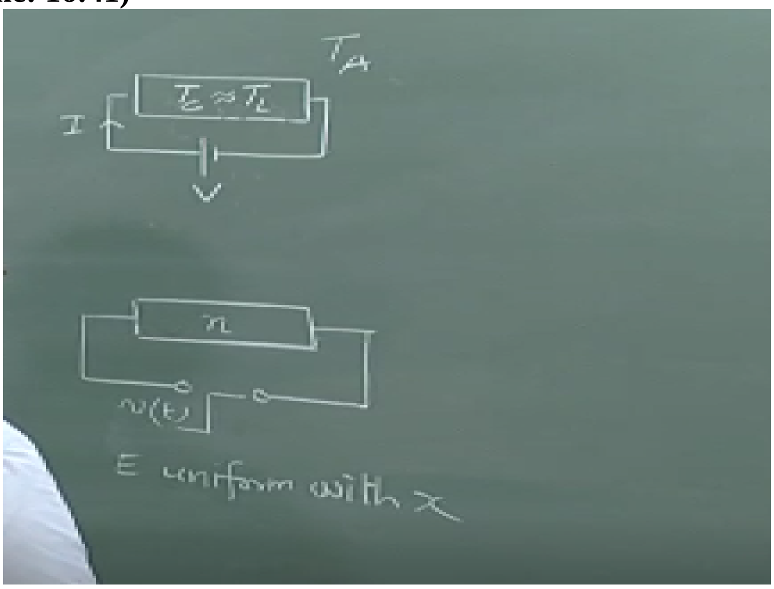

So in fact. It is similar to this so this is the semiconductor will assume it is a uniform semiconductor. Further let us assume this is n between these 2 points certainly they are applying a step in the voltage so this is V as a function of time Okay. This voltage step is large this is a conceptual situation okay when you apply such a large voltage a large current can be there and so you have to cool the sample and so on.

So this experimental set up we are not discussing here so we apply a sudden step in the voltage. As a result, there is a sudden step in the electric field now the electric field is uniform throughout the sample please understand this so E uniform with. X. So it is varying with T because the voltage step is varying with T, but always from this end to that end the electric field is uniform. Okay.

So that is the situation and what we are monitoring is this current which will follow the drift velocity characteristics now returning to the slide. So this is your electric field step inside the sample and here we show the Carrier energy as a function of time which is a consequence of energy balance now we need to explain an important point here why do we start with energy balance.

Now, you know that we have to use energy balance momentum balance and carrier a balance all the 3 to explain any of these phenomena the important point is that we must start with. That balance consideration where the time constant associated with the relaxation is highest so which ever process is slowest we have to start with that balance consideration. For example, you know that carrier a balance.

So if there are excess carriers and they have to relax. Then the time constant associated with relaxation of excess carriers is minority carrier life time. Time constant associated with the relaxation of momentum in momentum balance considerations is momentum relaxation time. Whereas the time constant associated with energy relaxation in energy balance is energy relaxation time.

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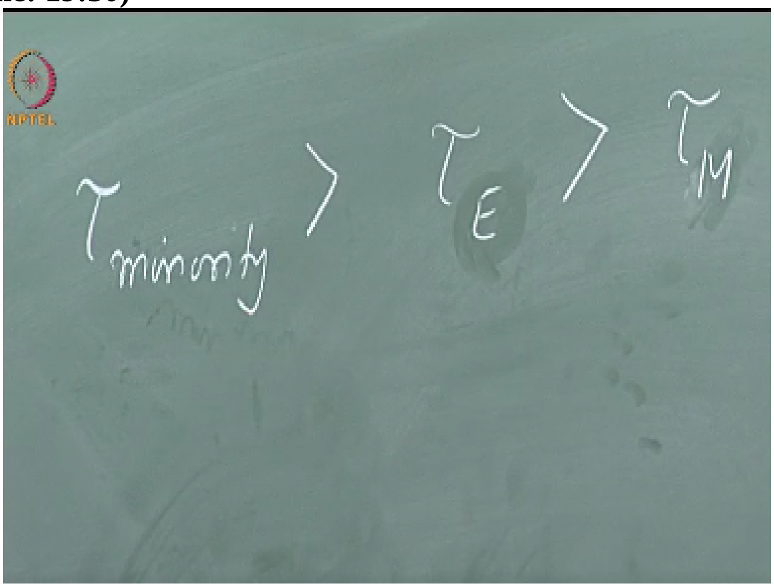

So if you look at these 3 time constants namely the minor to carrier a lifetime the momentum relaxation time and the energy relaxation time then we know that the order of magnitude of these quantities are as follows The minority lifetime is the largest. Then comes the energy relaxation time and then the momentum relaxation time. So what is the meaning of this the excess carriers relax at the slowest rate.

The energy relaxation is faster than relaxation of. excess carriers and momentum relaxation is the fastest. So if all this 3 processes are present then the carrier balance equation is the one that one must start with okay now in our present case. The carrier concentration is constant with time so there is no question of carrier relaxation. Therefore, in our present situation we are left with the energy relaxation and momentum relaxation.

And energy relaxation time is more slower than momentum, so energy relaxes much more slower than momentum so whichever is the slowest process of relaxation. We must start with that because the faster processes can adjust with the slow process. Okay so generally the behavior of the slowest process will be simple. So we start with that and other processes which are faster adjust with the slowest process.

So in this case since carrier balance considerations are not important because the carrier concentration is constant with time and it is equal to the equilibrium value. We start with the energy balance consideration, okay now

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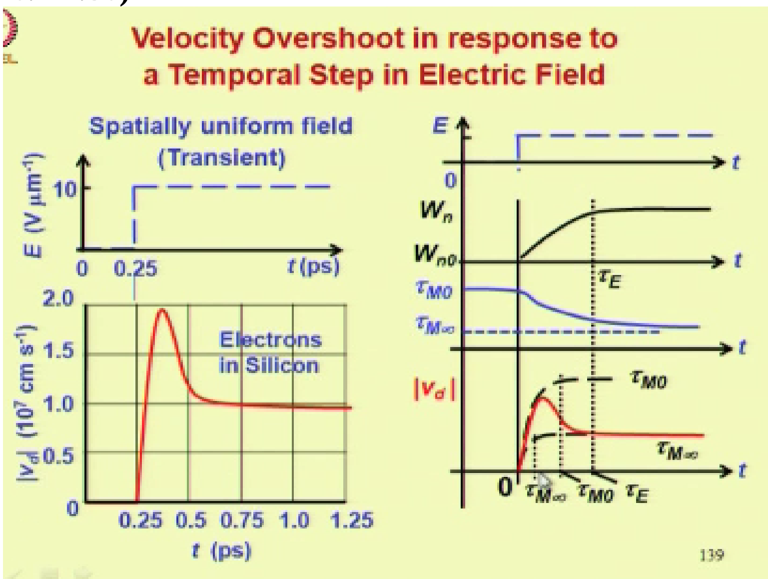

So energy changes. From WN0 under equilibrium to the saturation value in the order of energy relaxation time, now please note here we are only considering the order of magnitude of the quantities if you are. Going to be if you want to be very precise. Maybe it will be 2 or 3 times energy relaxation time, okay that will be the duration of this transit. So right now, we will only be concerned about the order of magnitudes when we talk about the equations introduce equations then we will make this duration more precise.

So the energy is increasing and then saturating consequently see what is happening to the momentum relaxation time. The momentum relaxation time is decreasing from equilibrium dou 0 to the value of dou m infinity because as we have discussed earlier the momentum relaxation time is a function of carrier energy and higher the carrier energy lower is the moment of relaxation time because the scattering rate is more at higher energy.

It is this variation of the momentum relaxation time. That is crucial to explanation of the velocity overshoot so as we will see the fact that momentum relaxation time is very different from the energy relaxation time. It is much shorter than the relaxation time. This will be important for us to explain the velocity overshoot now let us see what are the consequences of variation of the momentum relaxation time, so here is the velocity curve.

Which is a consequence of the momentum relaxation time. Now for First view this curve and this diagram looks a little complex there are many things shown here so let us develop this curve on the blackboard.

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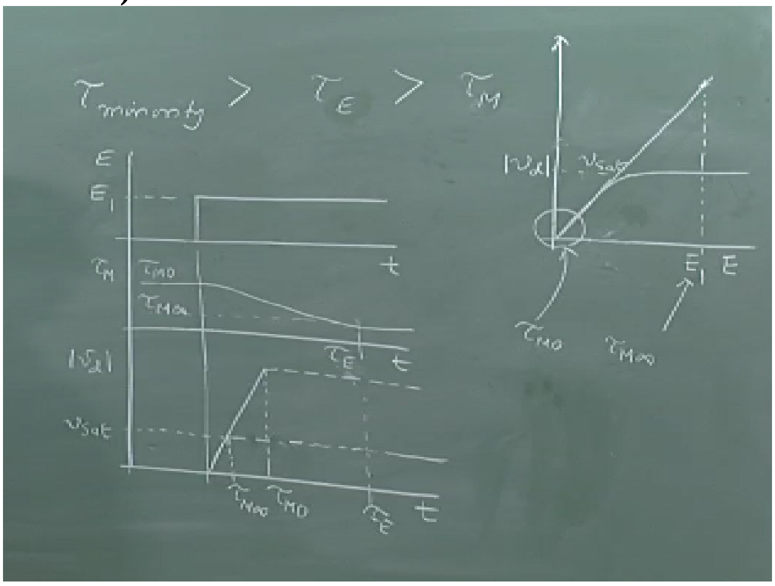

So let us say the electric field step. At this instant this is as a function of T and the momentum relaxation changes like this. Like this now it will remain =dou M0 for some duration. Until the energy really starts increasing and that is where it starts falling so let us say it falls like this and this duration is of the order of the energy of relaxation time. And this value is 2 M infinity okay now we want to develop, so this is.

Where we want to develop. Drift velocity versus time curve, let us refer to the drift velocity versus field curve for a steady state conditions so you will recall the velocity field curve was something like this okay this is under steady state evidently. So you will get this curve if you are increasing even very slowly and allowing the device to restudy state for each condition. Now, this is the magnitude of our electric field step.

Let us see steady state conditions what would be the velocity for this electric field. So if I show this. Value as E1 and mark of this value here let us say E1 is coming somewhere here say this is E1. So corresponding to E1 this is your velocity so this is the so called saturation velocity we lost so under steady state conditions after the transients had relaxed you must achieve VSAT, so let us mark out the VSAT here.

So let us say this is your VSAT, now why does the velocity saturate, because corresponding to this E1. Your momentum relaxation time is dou m infinity there is a momentum relaxation time marked here and this momentum relaxation time depends on the electric field. So the velocity saturates because the momentum relaxation time in this region decreases inversely as the electric field.

So product of this and the electric field becomes a constant now so the momentum relaxation time corresponding to this value is dou M infinity. So we could say that if your momentum relaxation time was dou m infinity for the whole duration assume that immediately this system achieved momentum Relaxation time of dou infinity after you step it up then your curve for velocity would be something like this. So in this time which is 2 m infinity.

It will achieve velocity saturation, so this value, so this what would have been your curve, however we find that at least during the initial stage of the transient your momentum relaxation time is dou m0 and not dou m infinity. Let us see this duration. Dou m o corresponds to the momentum relaxation time in the field was really low, here, so on this curve. It is in this region, okay.

So if the momentum Relaxation time corresponds to the value here and your curve was increasing along with the electric field so for the same electric field. If the momentum like relaxation time was 0 then, you will achieve a velocity. As shown here you extend a straight line and this is your velocity that you will reach if your momentum relaxation time reaches to 2 m 0 which is the low electric. Okay.

So if you had your momentum relaxation time is Dou m 0. So let us draw the curve for this extreme. So for this extreme your curve would be so the curve would rise with time in the same way because the field is same acceleration the same certain rise but it will do so now for dou m 0. And then you will get this saturation velocity. Now based on this we can predict what will be the velocity versus time curve if your momentum relaxation time varies.

So evidently your curve should start on this particular velocity time curve should start on this curve and end on this curve it should end on this car after the duration of the transit that is energy relaxation time. So the curve would look something like this so it will go up and so it starts on this curve but then gradually moves to the other curve because the momentum relaxation time changes.

Now you can say. Why cannot I start on this curve and then end on the other cover right here why should I overshoot. Now the reason for this and this is an important point is. That the momentum relaxation time changes from Dou m 0 to dou infinity rather slowly over the energy relaxation time interval, if the change from dou m0 to dou infinity was very rapid if this energy relaxation time was very small of the same order as these times then the change of the curve from.

This curve to this curve would be very rapid and in fact you will not get any velocity overshoot. So the velocity overshoot is happening the curve is climbing on this particular curve corresponding to 2 m0. And this is corresponding dou m infinity. Because. The system is not relaxing fast it is taking time to relax therefore it climbs up much higher here before it starts to move down the velocity starts to move down okay.

So that is the reason now here we have drawn curves for dou m infinity and dou m0. To be having the same slope here whereas here this corners would get rounded off in practice so on, the slide a realistic curve is shown where this corners have been rounded off.

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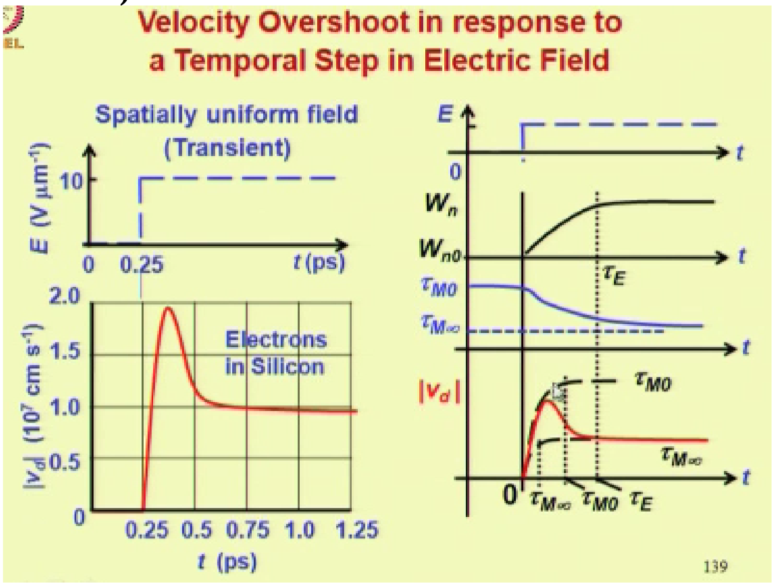

So let us look at this curve here. So you have seen this corners are rounded off now I want to emphasize that when we say, when we put the term dou m0 here we should not think that this is dou m0, so this axis is velocity what we are saying is this velocity time curve is assuming that the time constant remains same as dou m0 throughout the transient, so it is somewhat like plotting MOSFET curves, so you plot rain current versus rain voltage for different gate source voltages, so gate source voltage is a parameter.

Similarly, here dou m0 and dou m infinity are parameters, finally to complete the picture. Let us show the carrier balance. Consequences, so carrier balance consequences is that your concentration remains constant n0 as a function of time.

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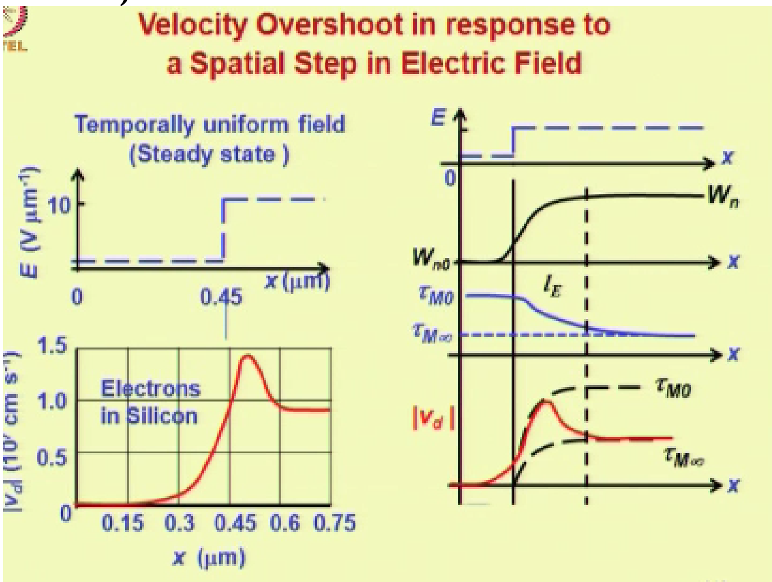

Now in the same manner let us explain the. Spatial velocity overshoot, so here are the relevant diagrams for the spatial velocity overshoot so the changes abruptly at some location to high value. And as a consequence the drift velocity varies as shown in this figure.

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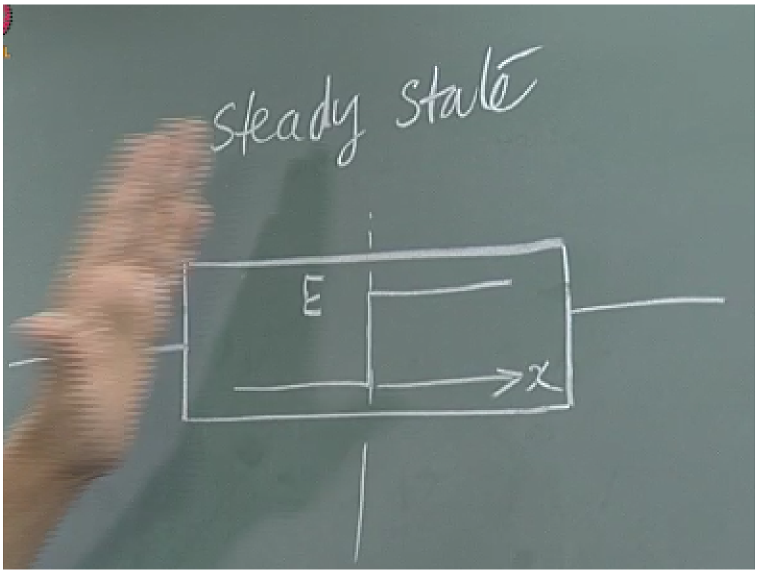

Let us draw a structured diagram to explain what is happening here so this is your semiconductor in which the field is suddenly step at some location. Now this is a steady state situation, please note that things are not changing with time unlike in the previous case. This is important because under steady state the current in the device will remain constant with X. And I Is the current entering the device, though the current remains constant.

In the device we will find the velocity is going to change the distance because of this step response and evidently the only way current going to mean constant is carrier concentration should also change in a compensating manner. To the velocity change so that the current remains constant so that is why in this case both the velocity and the carrier concentration both will change the distance.

So we are not bothered about how this electric field step can be brought about that it can be several ways of doing this just to make a short mention. You could probably put a delta doping here. Okay that can. Create a field step some sort of a charge in a short location. Let us look at the velocity response. So we find that. While the step occurs at 0.45 microns here the velocity starts increasing at 0.3 microns itself that is before the step.

Now you should not confuse this with a non-causal behavior so it is not as though things are when we say when we use the word before it does not mean it is before in time. It is distance so it is not a non-causal situation or un physical situation so such a curve would not be physical if this axis of time because that would imply the velocity is anticipating the change in electric field.

Which cannot happen in practice however when it is with distance the velocity can change before the location of the step in the field and will explain how this happens. So anyway the velocity reaches a peak value beyond the step and then saturates falls down and saturates. Now look at the distance over which the change is happening this is about 0.3 micron to 0.6 micron so about 0.3 microns is the distance over which the change happens and this 0.3 microns is distributed.

Part of it is before the step location and part of it is after the step location now let us explain this velocity overshoot following the approach for transit will also be overshoot we will start with the energy balance consideration in this case. Though, carrier concentration will change with distance since it is not changing with time there is no question of considering carrier relaxation the time.

So the slowest process in this case is energy relaxation momentum relaxation in this faster process so that is why we are starting with energy balance considerations so here is the change in energy as a function of distance. From the equilibrium kinetic energy WN0 the energy changes to a saturation new saturation value higher value. Over a distance LE. From the location of the change in the field step here the energy begins to rise before this location.

The reasons for which will become clear later right now as an approximation let us say it starts rising beyond this step. Now let us understand. A little bit about this distance over which the change happens now this distance can be approximated as the energy relaxation time over which the energy relaxation happens multiplied by the average velocity which can be obtained from this velocity distance graph.

So we could say for example when approximation the average velocity is about 1 in to 10 power 7. So this is 1 so this is average some region the velocity is higher and some of the reason it is lower so average is 1 in 10 power 7. So if you do a simple calculation. Energy relaxation time is about 1 picosecond. The average drift velocity just now we saw it was 10 power 7 centimeters per second transient duration. Multiply these 2, you get LE = VD dou e.

That is equal to 10 per -5 centimeters though this is the order is not the exact value, this is the order or 0.1 microns, now this is how we get. The order of the distance so here you can see so 0.45 to 0.6 is about 0.15 microns. So that is the LE, okay now you have the transient, not transient, I am the sorry the change even before this so that is why. The change occurs over a distance more than LE it is starting from here okay now based on this. Energy change.

We can plot the momentum relaxation time change so momentum relaxation time changes from time 0 to time infinity as in the earlier case except that now it is happening over a distance as the energy is changing over distance now exactly following similar arguments we can develop the velocity versus distance. So you have 2 extreme cases shown here. If your momentum relaxation time was dou m infinity throughout this duration.

Then you will achieve the saturation velocity. Corresponding to the velocity field curve
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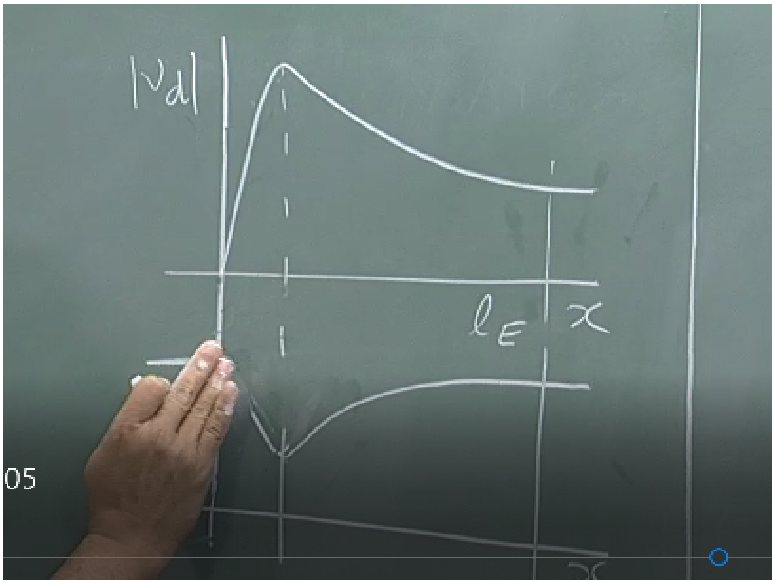

Now let us return to this same diagram this will also be field curve if the size of your step here. If this value is even, then corresponding to even. Under steady state conditions you will have this saturation velocity. On the other hand, supposing your momentum relaxation time was doum0 throughout that is this initial value the higher value then you will saturate at a higher velocity here so.

This is that higher velocity because in this region time is dou m0, if you follow this right up to the field even then you will reach here. So this would be a higher saturation velocity such a loss. So that is what is shown here so this is the other extreme curve now it is important to note that we are talking about distances and so you have to convert from time to distance so just as we converted from energy relaxation time to LE by multiplying the energy relaxation time by average velocity.

We can convert from the previous case of transient velocity overshoot from this time dou m0 and dou m infinity. The corresponding limits by multiplying with average velocity in this duration so that is how you get the length of this transient so in this case for example this transient occurs over a smaller length and this occurs over a larger length, okay so now following similar arguments your velocity field curve up should start on dou m 0 curve.

But ultimately saturate on the dou m infinity curve. Also this change from dou m0 to dou m infinity occurs slowly and therefore the velocity curve also be gets a lot of time to climb up. Along the first curve before it starts moving towards the second curve so that is where you get a velocity overshoot now it does explain why the velocity should start increasing earlier than this location okay.

That will also explain why the energy starts increasing before the location of the field step for that we need to go to the carrier concentration for this X curve. Which is shown here. So here you will find that the carrier concentration also is changing before this step now let us explain why this happens then based on this we can build up the variations of the velocity and the carrier energy.

So supposing I plot here the velocity versus distance suppose it is like this now since that current density J = q times the concentration times the velocity. If VD is a function of Then N also has to be a function of X. I because J should be constant So here we have said I should be constant with distance it is a steady state consideration I is nothing but area multiplied by J, okay So already a cross section of the semiconductor we are assuming that the current is uniform over this area so NX VDX.

So if VD is a function of X. N also the function of X, to compensate for this variation so that J. Is independent of X. It is a constant with X. So if I write sketch N for this I will get something like this, so this is the distance LE, now this Distance always this transition occurs is really a very short so this variation of the carrier concentration is very rapid causing large diffusion currents you know well carrier concentration would change as we dispense rapidly it will cause large diffusion.

So really it is not possible for carrier concertation which abruptly start changing beyond this point because that would mean a lot of different current just before that you find that the slope is o, okay so this is not possible so what happens is there for this carrier concentration corner change becomes smooth and out so that such large diffusion currents do not arise. And so this becomes something like this.

So now you see that is the reason why before the step in the field here. If I plot, the field step it will look like this. Before the step in the field your carrier concentration has started changing so that this variation is gradual to keep the diffusion current under control not become too high now again by the same rule. Whenever N is changing with X. VD also should change with X.

So VD with X earlier because N has started changing with X earlier because this gets smoothened out here like this and similarly because of this reason the kinetic energy curve also gets smoothened out. And it starts changing before the location of the field step, so this explains the complete velocity versus distance curve. Now we need to explain commonly used terminology related to velocity overshoot the kind of velocity overshoot we have discussed it is called in non-local phenomena.

Now why should it be called a non-local phenomena that is what we explain next.

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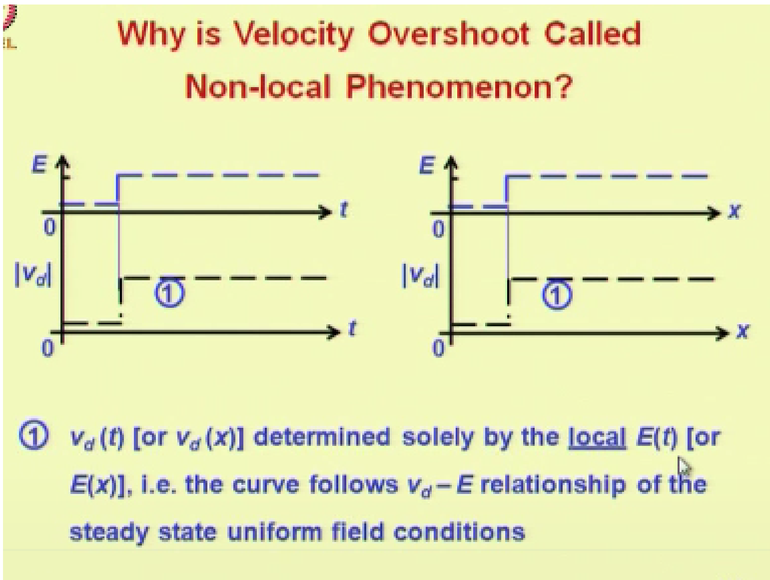

Both forms of velocity overshoot are shown here so as a function of time and as a function of. distance. Now suppose the velocity versus time or distance curve was decided by the local value of the electric field in other words if it was decided based on this velocity field curve that we have drawn here which corresponds to steady state actually it is not correct but supposing we used this curve to predict.

Then your velocity versus time or velocity versus distance curve would be an abrupt change. Okay so in other words, as written in the slide if VDT or VDX. We were determined slowly by the local electric field that is E at that time instant or E at that location so the world local means the value at that particular location in time or distance. That is the current follows the VD relationship of the steady state uniform field conditions.

So if the velocity were determined by the local electric field local in time or distance then you would get an abrupt change whereas actual situation is this. So velocity curve does not follow the electric field at that point. So the actual non-local velocity profile where VDT or VDX is not determined solely by a local ET or local EX. So this is why the curve too is referred to as non-local curve one would be referred to as local phenomena whereas curve 2 the velocity let us say at this instant does not depend on the field at that instant right.

So then that is the reason why it is called non-local now here is a simple analogy to explain. How the word nonlocal arises okay something that is something which we are more familiar with so the carrier concentration in a semiconductor equilibrium which is not uniformly doped. So the majority carrier concentration is not = NDX. NX does not follow NDX, if NDX varies rapidly with X.

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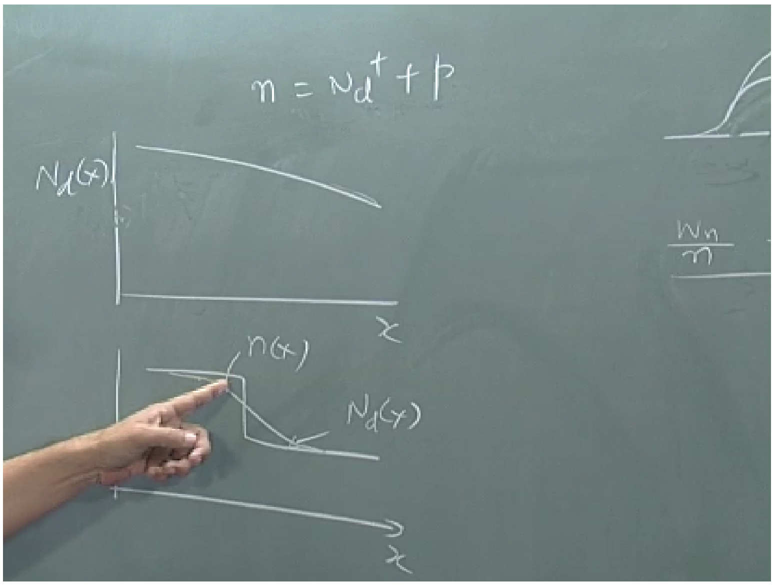

So here is an example supposing you were Nd(x) very slowly like this with X. So this is Nd(x). Then your n(x) will also follow almost the same because your formula is N=ND+P, okay and minority carrier concentration is small so N follows Nd and Nd+ but suppose you had a situation like this. So same curve will also correspond to n(x) here. There is a rapid change in Nd. So this is Nd(x) curve then your mobile carrier concentration n(x)would change like this.

So this is your n(x) curve, so now you see at this point the n(x) != Nd. So this curve is not following this curve therefore we can say this is non-local phenomena right so n(x) is not following the local Nd(x).

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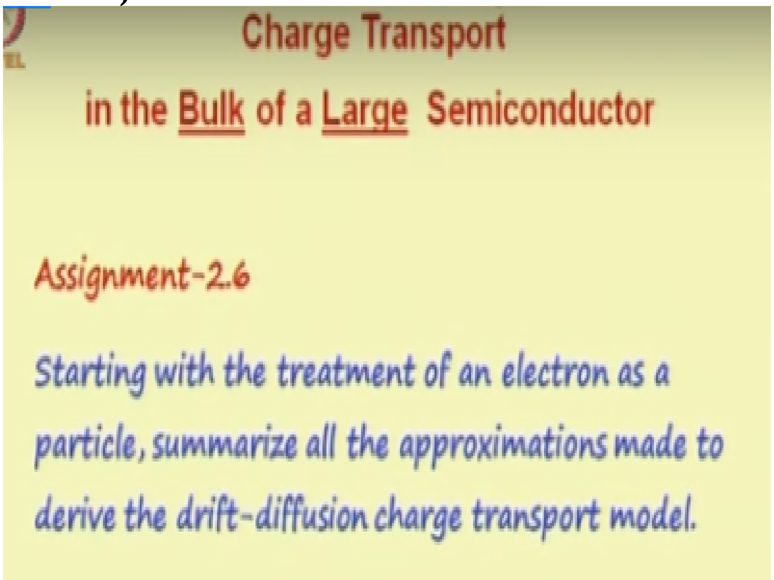

So now let us look at a few assignment questions for you. Starting with the treatment of electron as a particle, summarize all the approximations made to derive the drift diffusion charge transport model, so we have come to the end of this model and end of this lecture so that is why this is an assignment which tries to trace all the approximations which we have made to arrive at the drift diffusion transport model.

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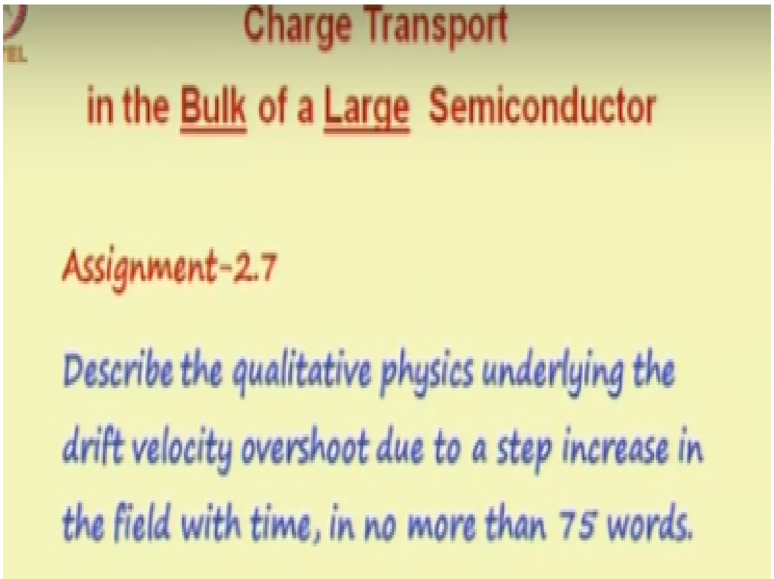

Another assignment is described the quality or do physics underlying the difference to be overshoot due to a step increase in the field with time in no more than 75-watts so transient would also be overshoot you tried to capture in 75-watts. Okay, not more than that. So whenever you have a right. Or explain something within a few words you really have to spend a lot of time in clarifying the understanding and making it perfect.

In fact, I can give you a quote at this point a famous scientist Pascal once said while writing a letter that I am writing a long letter since I do not have time to write a short one so whenever you want to write things precisely and briefly then you have to spend a lot of time in clarifying your understanding so that is the goal of this assignment.

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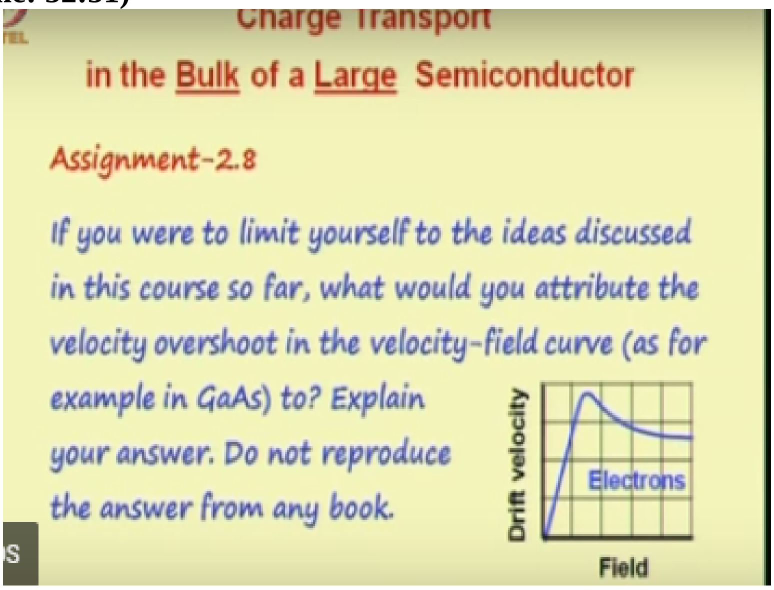

Then if you have to limit yourself to the ideas discussed in this course so far. What would you attribute the velocity overshoot in the velocity field curve as for example in gallium arsenide 2 so the velocity overshooting and velocity field curve, explain your answer do not reproduce the answer from any book so assuming that you know whatever we have done in the last 4 or 5 lectures.

And that is all you do not know anything more then what would be the reason that you come up with this kind of drift velocity versus field curve or electrons. So there is a modification of this curve here there is a saturation but for gallium arsenide it goes up and then comes down.

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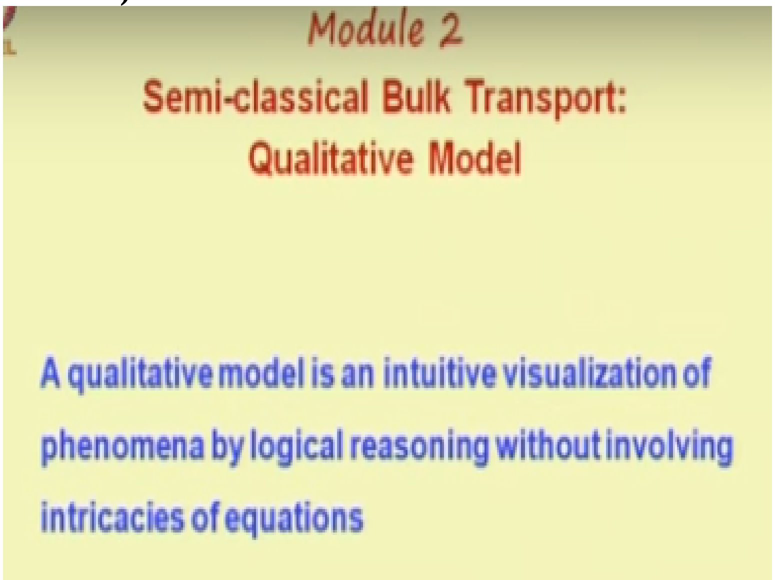

Now let us summarize this lecture and the more you have some key points. So this module discussed qualitative modeling of semi-classical bulk transport, a qualitative model is an intuitive visualization of phenomena by logical reasoning without involving intricacies of equations.

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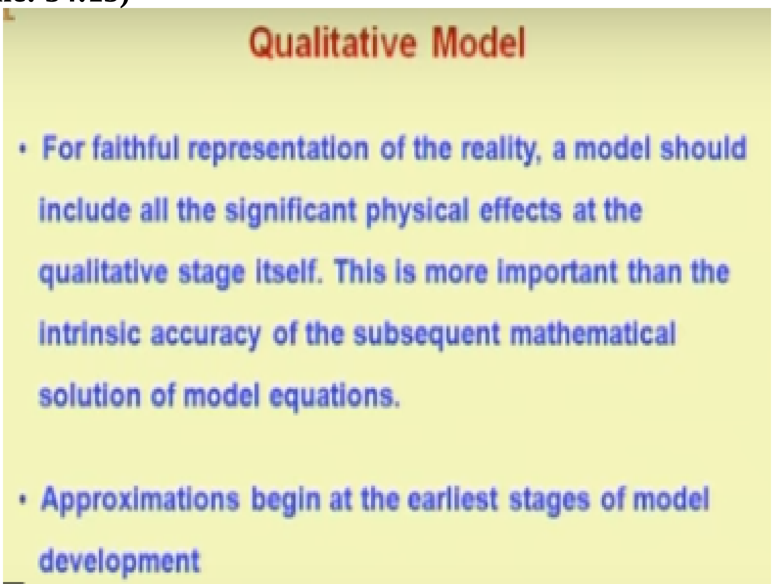

Then, we made the important point about qualitative modeling namely for faithful representation of the reality a model should include all the significant physical effects at the quality stage itself this is more important than the intrinsic accuracy of the subsequent mathematical solution of model equations. Approximations begin at the earliest stages of model development.

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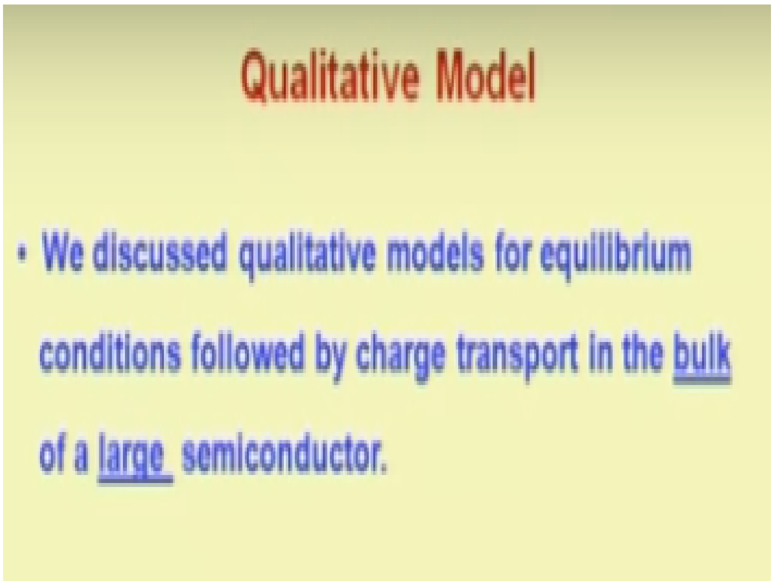

We discussed qualitative models for equilibrium conditions followed by charge transport in the bulk of a large semiconductor.

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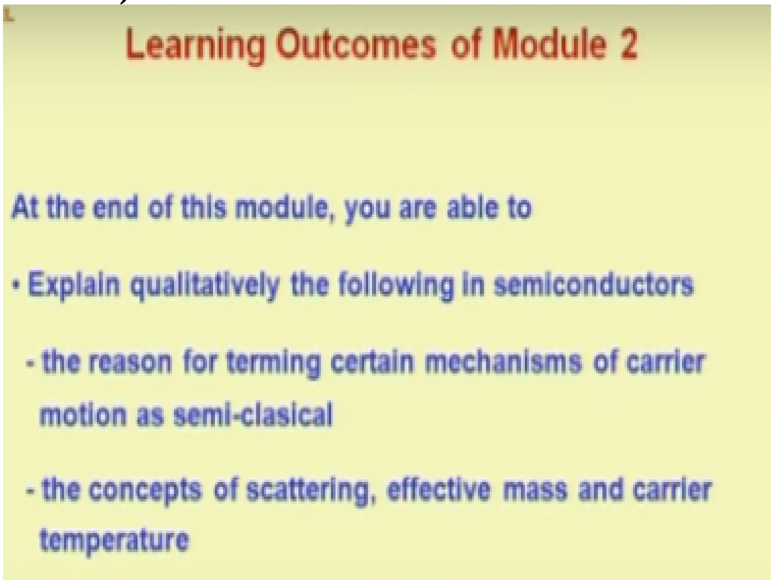

Learning outcomes of this module so we had said in the beginning of this model that by the end of this model you should be able to do a few things so now you can check whether you are able to do these things so this list tells you more in more detail what are the important points that we covered so at the end of this module I hope that you are able to explain qualitatively the following in semiconductors the reason for terming certain some mechanisms of carrier transport are carrier motion as semi classical.

So we said that between 2 collisions are scattering events the carrier can be treated using Newton laws but the scattering event itself has to be treated quantum mechanically and be explained why Also we said that when we use Newton's laws to model the motion between 2 collisions the mass of the electron is hole is not the same as mass in vacuum is an effect to mass that captures the effect of the periodic that is potential.

And this effect to mass also has to be derived from quantum mechanics because the potential variations which give rise to this effective mass occur very rapidly over lens which are very small compared to the wave length, so because if I am scattering how did quantum mechanically there is no fully classical treatment of carrier transport and that is why carrier transport is called semi classic.

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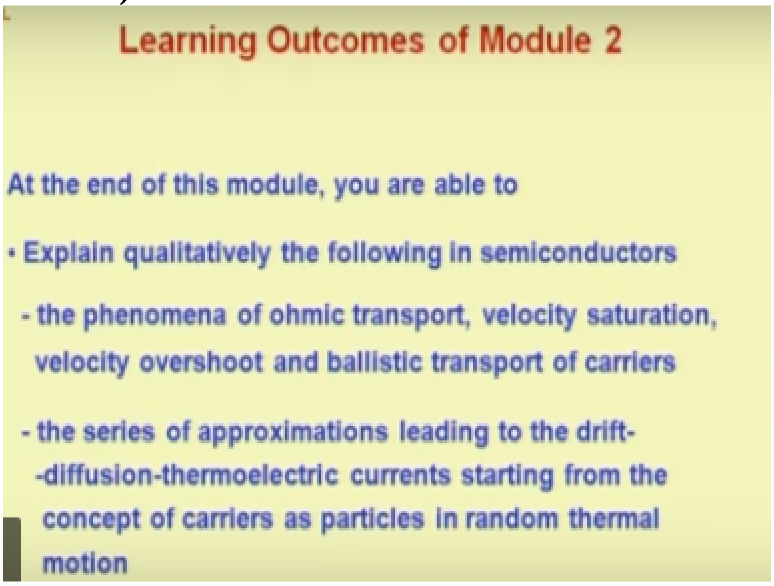

We discussed the concepts of scattering effective mass and carrier temperature in detail. Then I hope that you are able to explain the phenomena of ohmic transport, velocity saturation, velocity overshoot and ballistic transport of carriers. And finally you should be able to explain the series of approximations leading to the diff diffusion thermos electric currents starting from the concept of particles in random thermal motion.

While we point out that we have not considered the range of validity of the particle approximation and the conditions under which the particle approximation is valid so this point we will discuss in detail in a later lecture, however we have mentioned that the semi classical transport is valid when the device size is sufficiently large so that there are a large number of scattering events. And there are sufficiently large number of electrons and holes in the device.