Semiconductor Device Modeling
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Lecture - 06
Semi-classical Bulk Transport: Qualitative Model

In the lecture, so far we have discussed the semiconductor under equilibrium, then we discussed how a directed motion can be superimposed over random thermal motion, which is present under equilibrium. The driving forces which cause this directed motion are the electric field, the magnetic flux and the heat flux. We made certain approximations for the various flows that together account for the current in the semiconductor.

So we said that the current in semiconductor can be regarded as a consequence of 6 fluxes which are coupled to each other or 6 flows which are coupled to each other, 3 of these are driving forces that is electric field, magnetic flux and heat flux and the consequences namely the electron flux, hole flux and the displacement current. So since this picture is complicated we made some approximations related to each of these fluxes.

For example, we neglected the magnetic flux, we said we will neglect the heat flux and we will assume that the electric field varies very slowly with time in other words, we make the quasistatic approximation for the electric field. Then coming to the electron hole flux, we said that these fluxes will be estimated using particle approximation, then using effective mass approximation, in which we regard the electrons and holes to have an effective mass different from the mass in vacuum between any 2 collision or 2 scattering events in the semiconductor.

And thirdly we said that even though the energy, momentum and the concentration of carriers is distributed, in other words there is a random distribution of these quantities we will assume that within a local volume of a semiconductor we shall assume the quantities namely the carrier concentration, the momentum density and the carrier energy density to be uniform at the average value within the local volume.

And then we said as a consequence of this approximation we will able to analyse the current flow in semiconductors based on the familiar conservation laws namely the mass conservation law or the carrier balance equation, the momentum conservation law or the momentum density balance considerations and the energy conservation law or the carrier energy density balance considerations.

Now based on these, let us proceed further to discuss the charge transport in the bulk of a large semiconductor.

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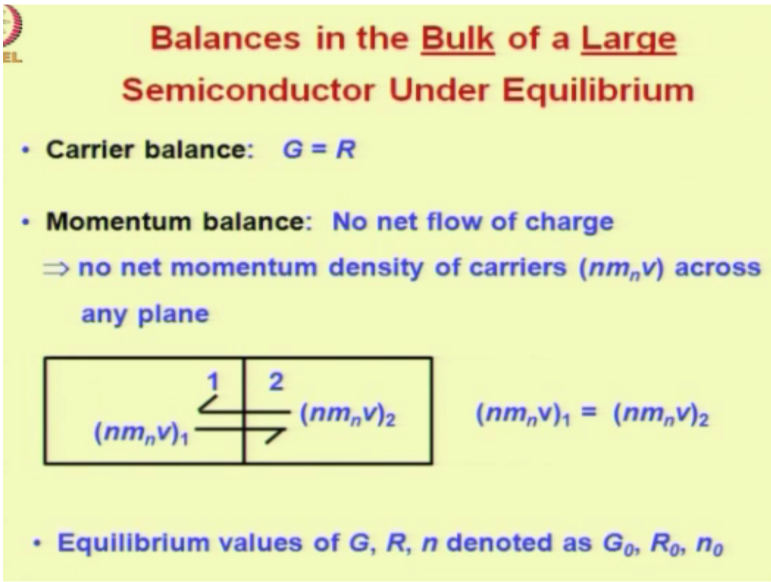

Let us consider the balances under equilibrium. So we will proceed in the same way as we have done so far. First we will discuss the equilibrium case and then we will discuss the directed motion superimposed over the random motion. So what are the balances under equilibrium, the carrier balance, the statement that generation rate is equal to recombination rate is the statement of carrier balance.

What is the statement of momentum balance, so we said equilibrium means no net flow of charge. Now this is actually a statement of momentum balance or momentum density balance. So no net flow of charge implies no net momentum density of carriers which is given by the relation n into Mn into V, n is the concentration of electrons Mn is effective mass of electrons and V is the velocity of the electrons.

Now as we have said earlier that we will concentrate on the electrons and whatever we said for electrons would be valid for holes also. So the net momentum density of carriers across any plane is 0, pictorially this is shown by the diagram here. So this is a semiconductor, you take any plane so you divide this semiconductor into 2 parts 1 and 2. There is a momentum flow from 2 to 1, that is shown by this arrow and from 1 to 2, that is shown by this particular arrow.

Now let us use a nomenclature in which the starting point of the momentum flow is given as suffix here, so nMnV suffix 2 indicates the momentum flow from 2 to 1 and similarly nMnV suffix 1 indicates the flow from 1 to 2. So we are looking at an idealised 1-dimensional case. Now we have said that equilibrium is the case of intense activity. So therefore there are flows, but for every process there is an inverse process going on at the same rate, that is what this diagram shows.

So the statement of momentum density balance is nMnV1 = nMnV2. Now let me just clarify that whenever we use the term carrier balance, it means carrier density balance. Whenever we use the term momentum balance it means momentum density balance. So this should always be born in mind. Similarly, energy balance is energy density balance. Now let us look at the energy balance under equilibrium or energy density balance.

Now before we do that let us get familiar with the nomenclature. The quantities generation rate recombination rate and electron concentration or carrier concentration are denoted by the suffixes 0, so G0, R0, n0. So the moment we put a suffix 0, you must regard this particular quantity to be representing the value under equilibrium.

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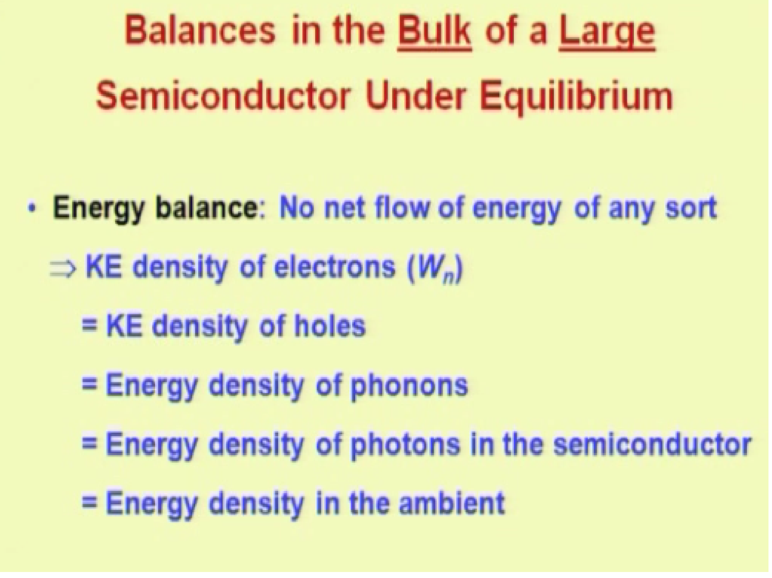

So going to the energy balance, we have made the statement while defining equilibrium that there is no net flow of energy of any sort. So that is actually a statement of energy balance. So this means kinetic energy density of electrons which we shall use the symbol W suffix n to denote is same as kinetic energy density of holes is same as energy density of phonons, is same as energy density of photons in the semiconductor and is also the same as energy density in the ambient.

So please take careful attention to the statement of energy balance. So what we are saying is the following:

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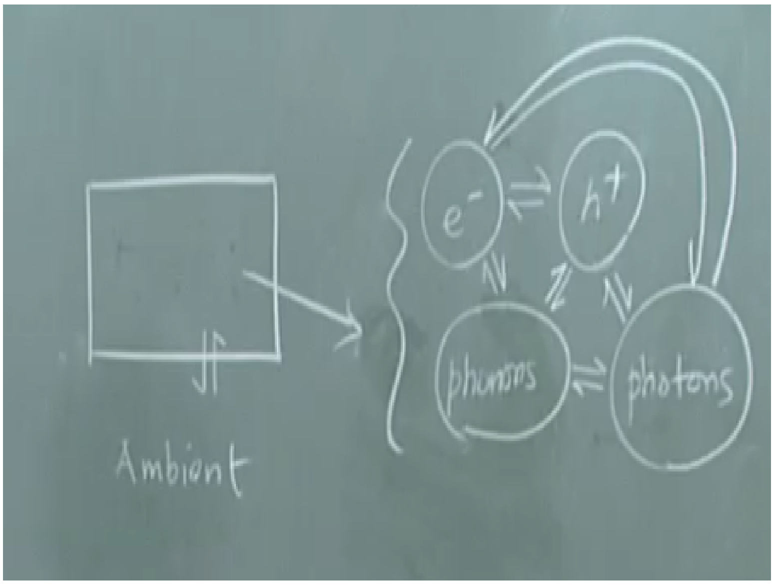

So suppose this is the semiconductor and this is the ambient. Now inside the semiconductor you have populations of electrons, so conceptually let me show them separate. So electron, holes then phonons, photons, so this is inside the semiconductor, right, you can have photons outside also. So in ambient you can have photons, right so that is why it is important to regard that here we are talking about photons inside the semiconductor. Now these are the populations.

This is conceptual pictures, because really here if you see, spatially it is not as though some part is electron, some part is holes, some part is phonons, some part is photons, no. They are all mixed up, so conceptually what we are saying is energy density of this population is same as energy density of this population. For this population the energy density would be kinetic energy density and this is same as energy density of this population and energy density of this population.

So that there is no net exchange of energy from any one population to any other population, right. So even though there is energy exchange, yes certainly, because this is an equilibrium state an active state, dynamic state. But there is no net flow of any sort, right. So this is the statement of equilibrium. A student has a doubt here. Should there will be energy transfer or interaction between expression forms.

Your doubt is regarding this figure, here in fact that is a good point you have made, I should have shown an energy exchange between holes and phonons also. In fact, there is an energy exchange, now that you have said, between every 2, so we can have energy exchange between electrons and photons as well. So I should in fact show, something like this, like that. So there should be an arrow between every pair of entities here.

So electron hole, electron photon, electron phonon, hole electron, hole phonon, hole photon, photon phonon, photon hole, photon electron, right. So thank you for that. So let us proceed further with the discussion, the nomenclature, equilibrium value of Wn is denoted as Wn suffix 0. So with that we have completed the picture of balances, under equilibrium, the carrier balance, momentum balance and energy balance.

Now let us do the same exercise and explain how we can come up with the various mechanism of transport. So how does a directed motion gets superimposed over random motion.

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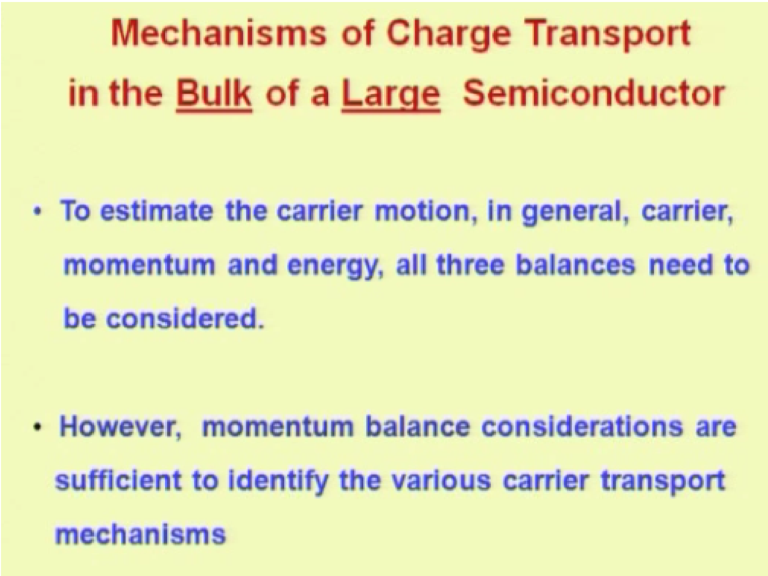

To estimate the carrier motion in general, carrier momentum and energy all 3 balances need to be considered. So carrier balance, momentum balance and energy balance all this have to be considered if you want to analyse completely the carrier motion. However as shown on the slide, momentum balance considerations are sufficient to identify the various carrier transport mechanisms.

So we can consider the momentum balance alone and then we can explain how there can be different ways of superimposing a directed motion over random motion, let us see that, how.

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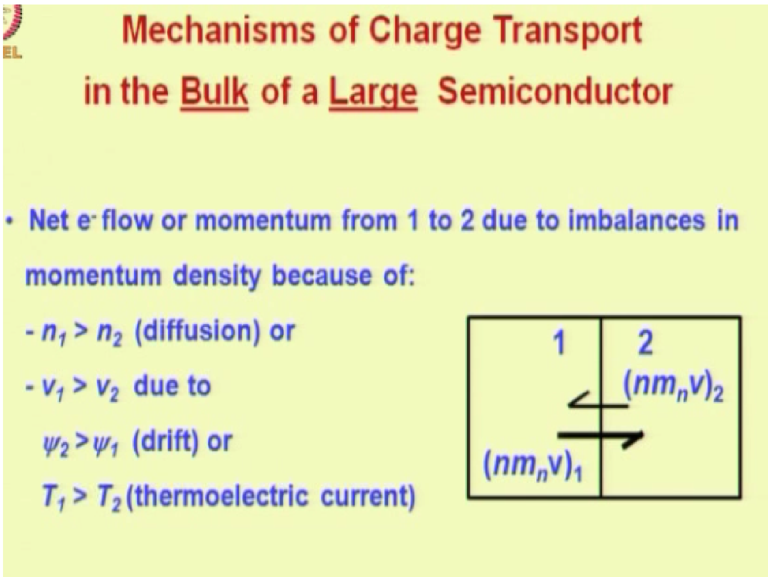

Now the figure here shows that flux from 1 to 2 is more than the flux from 2 to one. Therefore, there is a net flow from 1 to 2. Now how can such a difference be brought about. So the net electron flow or momentum from 1 to 2 due to imbalances in momentum density can arise because of n1 more than n2. So you can see that in this product, if n here is more than n here, n in one is more than n in 2, the momentum from 1 to 2 will be more.

Similarly, if V1 is more than V2, if the velocity here is more than the velocity here, then also there will be a net momentum from 1 to 2. Now the velocity can be more in one than 2, because of 2 reasons, either the potential in 2 is more than potential in 1, which causes a drift current or the temperature in one could be more than the temperature in 2 which can cause the thermoelectric current.

Now here we can regard the temperature as lattice temperature but later on as we will see we will introduce the concept of carrier temperature and strictly speaking the T1 and T2 shown on the slide should be regarded as carrier temperatures. So you see we are able to explain the diffusion drift in thermoelectric currents based on the simple model momentum balance.

So I should slightly reword my statement not that we are able to explain the entire current flow, we are able to explain how directed motion can be super imposed, that part alone we can explain based on momentum considerations.

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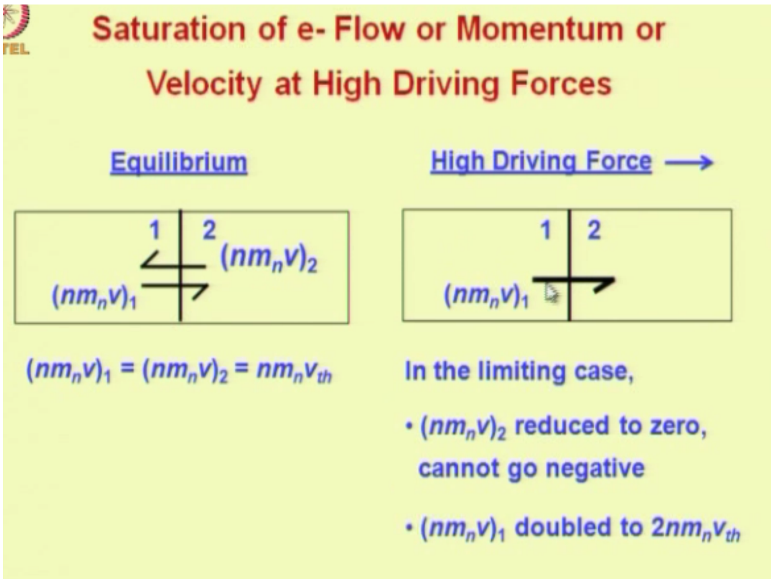

Let us similarly explain how we can explain velocity saturation. So velocity saturation is the same as momentum saturation, because momentum density is given by the velocity into the carrier concentration into the effective mass of the carrier. So we will use velocity and momentum density these 2 words interchangeably, sometimes. So saturation of electron flow or momentum or velocity at high driving forces how does it arise.

So the slide shows the equilibrium case first, so here nMnV1 is = nMnV2 = nMnV thermal, okay. So under equilibrium you have the thermal velocity and that can be regarded as velocity in region one and region 2. Now under high driving forces the picture changes as follows. So let us take the limit of the high driving forces, what a force has done, the force is applied from 1 to 2.

So what this force has done is this has accelerated or increased the motion from 1 to 2, but it has opposed the motion from, so force is like this it has oppose motion from 2 to one, because the force is against this motion. So in the limiting case as shown in this diagram nMnV2 that is this quantity reduces to 0, but you see it cannot go negative, because going negative means a flow from 1 to 2.

So at most the quantity from 2 to one can reduce, reduce, reduce and then go to 0. In the process what would happen is that the flux from 1 to 2 that is nMnV1 will double to 2nMnV thermal, because the same force which completely removes this flux adds as much flux from 1 to 2, and therefore the flux doubles. Now please note that this is an approximate picture in practice the flux will not exactly double.

Because according to this simple analysis your velocity saturation should occur at 2 times the thermal velocity. But that is not really true, the velocity saturation does occur for velocities of the order of thermal velocity, but the factor is not exactly 2, because we have to do a more regress analysis to explain that result.

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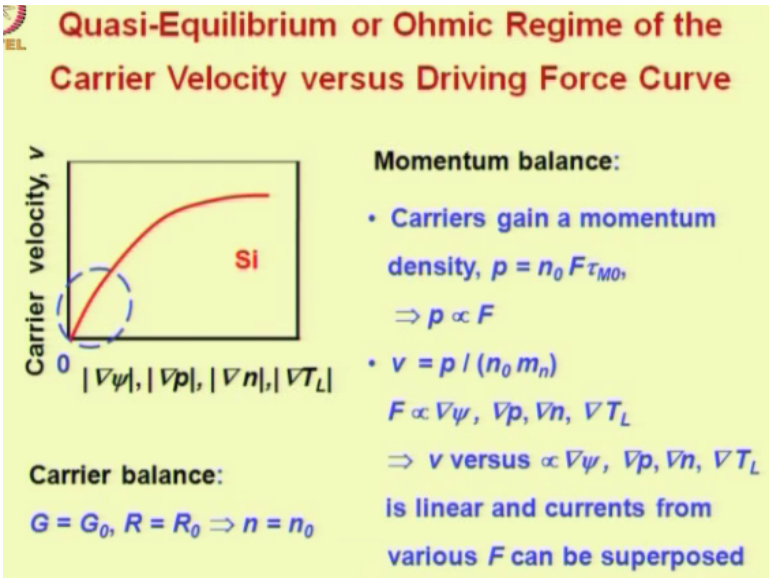

Now let us proceed further and explain the quasi-equilibrium or Ohmic Regime of carrier velocity versus driving force curve. So this is the regime that we want to explain has been circled here, so after qualitatively explaining how directed motion can be superimposed over random motion. We want to now become more precise in our qualitative reasoning and really explain the shape of the curve, why it is linear for small driving forces.

And why the curve saturates for large driving forces, we want to be more precise about our explanations. Now let us do this exercise in terms of the carrier balance, momentum balance and energy balance. So the carrier balance, the statement is G = G0, R = R0 and implying n =

n0. So if your generation recombination rates are not affected as compared to equilibrium, then carrier concentration remains at the equilibrium value. Now this is true because it is quasi-equilibrium, in other words very small disturbance from equilibrium.

Now this region is also called Ohmic, because it is like Ohm's law current is linearly related to voltage. Let us look at the momentum balance, the carriers gain a momentum density P = carrier concentration n0 into the force into the time for which this force acts to increase the momentum, that is the momentum relaxation time. The suffix 0 here means that it is the momentum relaxation time under equilibrium.

So again we are using the fact that disturbance from equilibrium is small. The reason why tau M can be assumed to tau M0 is that the energy disturbance also is small and this will take up next. Let us complete the momentum balance picture, so force into time is the momentum and multiply that by the concentration to get the density. So, hereafter unless stated otherwise the symbol small p, or lower case p will represent the momentum density of carriers.

The carriers gain momentum only during the free flight between 2 collision or scattering events, the moment a carrier scattered it loses its momentum, that is the assumption we are making here. So consequence is that the p is proportional to F, here F means the driving force, so which is related to the potential gradient or concentration gradient or the temperature gradient.

Again here we are putting the lattice temperature on this axis, but more strictly speaking when we introduce a carrier temperature concept, we will use the carrier temperature instead of the lattice temperature. Now if p is proportional to F, because p = n0 F on M0, then let us see what is the consequence. Now velocity is given by the momentum density divided by n0 into effective mass, and you know that the force is proportional to these gradients.

So if you club this statement, p proportional to F, V = p/n0Mn and F proportional to this gradients, we derive the conclusion that the velocity v versus these gradients should be linear and currents from the various forces can be superimposed. So that is the crucial result that we get, that the velocity is linearly related to the driving forces. And if multiple driving forces are present, we can simply sum up their consequences to get the overall velocity.

Now let us look at the energy balance picture, so carriers gain an energy density between collisions given by the carrier concentration n not into the velocity of the carriers into the force into the energy relaxation time. So the energy density is force into velocity, we know that force into velocity, or the momentum that is force into time is the momentum, you multiply that by velocity, then you get the energy.

And since it is energy density, you are multiplying it by the concentration. Now one important point to note here is that the time constant that is used here is energy relaxation time which is different from the momentum relaxation time used for finding out how much momentum a carrier gains between 2 collisions. We have introduced the concepts of energy relaxation time momentum relaxation time and mean free time between collisions earlier.

We have pointed out that momentum relaxation time is more than the mean free time between collisions, because not all collisions result in randomisation of momentum in all directions. So there are some collisions which only deflect the carrier very little, therefore they do not affect the momentum that much. So carrier has to undergo more collisions to lose the momentum, then it has to undergo even more collisions to lose the energy.

So the appropriate time constant should be used, when we are talking of how much momentum a carrier gains we must use the momentum relaxation time and we want to calculate how much energy the carrier gains or losses. Then we have to talk in terms of the energy relaxation time. So this quantity n0 into velocity into force into tau E0, because we are talking of quasi-equilibrium.

So this quantity is much less than the kinetic energy density of carriers under equilibrium. So this is really a statement of quasi-equilibrium, so if you want to convert the quasi-equilibrium statement into an equation, it would really mean this relation, that the kinetic energy gained between 2 collisions is much less than the equilibrium kinetic energy density. So this means Wn is approximately = Wn0.

Wn is the kinetic energy with the force applied, and this is also approximately equal to energy density of phonons and is also approximately equal to the energy density of the ambient. So really there is no net exchange of energy between any of the populations with in the semiconductor. Now just going back to this diagram, so we said this is the picture under equilibrium and in fact I should have added one more arrow and that from the semiconductor to the ambient also there is no energy exchange.

So you put all these populations inside here and then show one arrow from ambient to each of these population, that is what is a picture under equilibrium and the same picture also continues under quasi-equilibrium. Now therefore the argument so far imply that negligible net flow of energy from carriers to phonons to ambient. And therefore also the scattering rate is unaffected.

So because the energy density of carriers has not changed, the scattering rate which depends on energy is also not affected, please recall that we have mentioned earlier that the momentum relaxation time or energy relaxation times are related to the scattering rates and this scattering rate has to be derived from quantum mechanical considerations, and they depend on the energy density of the carriers.

So since scattering rate is unaffected the momentum relaxation time is same as that under equilibrium, the energy relaxation time is same as that under equilibrium. So this is thus condition of energy balance.

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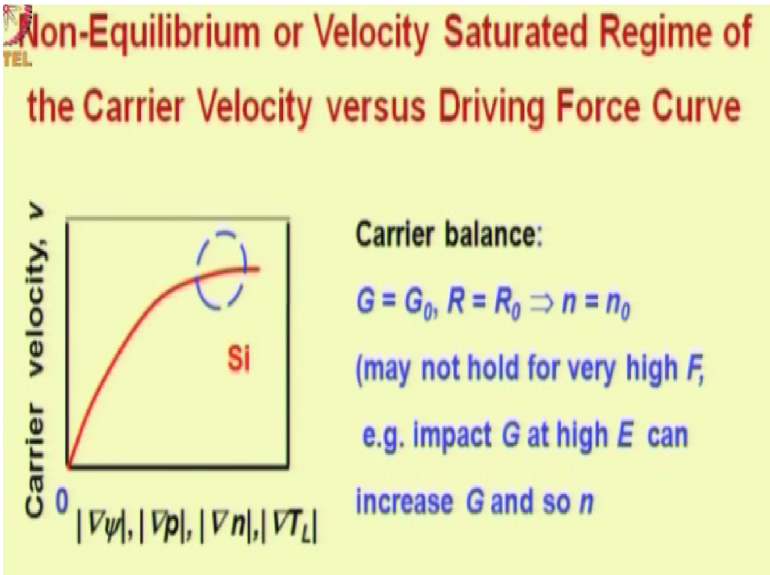

Now let us move on to explain the velocity saturation region, often this region is also referred to as non-equilibrium region, okay. So we divide the curve into broadly 2 parts one is a quasi-equilibrium where the curve is straight line, the velocity versus driving force curve is straight line. And the remaining region where the velocity versus driving forces curve is sub-linear and tends to saturate, so that region will be called non-equilibrium, okay.

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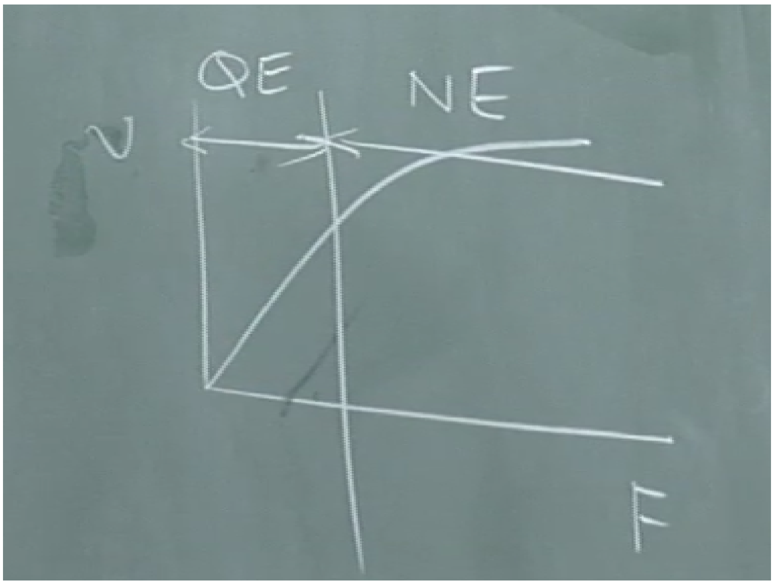

So something like this, so velocity versus force here so it is something like this. So we are dividing into 2 parts this is quasi-equilibrium and this region is non-equilibrium. Now the carrier balance under this consideration is same as under quasi-equilibrium that is G = G0, R = R0, and therefore n = n0. Now the comment is made here, that though in this particular case that we are discussing the generation rate or recombination rates are not affected.

If the force is very high as it happens for example, in the case of very high fields, then impact generation can be present, which will increase the generation rate and so it will increase the concentration n, so it would no more be = n0. In our case we are not entering into that regime where the generation rate is affected. The momentum balance, what is the momentum balance picture, so carriers gain a momentum density given by p = n0 F tau M.

So all that happen as compared to equilibrium is tau M has changed from tau M0, that is equilibrium value. Now where tau M < tau M0, momentum relaxation time is decreased since the tau M decreases as energy of the carrier increases. Now this is the result from the quantum mechanics, a simple way to understand this result would be as follows. The scattering depends on how many states an electron can scatter into from a given state.

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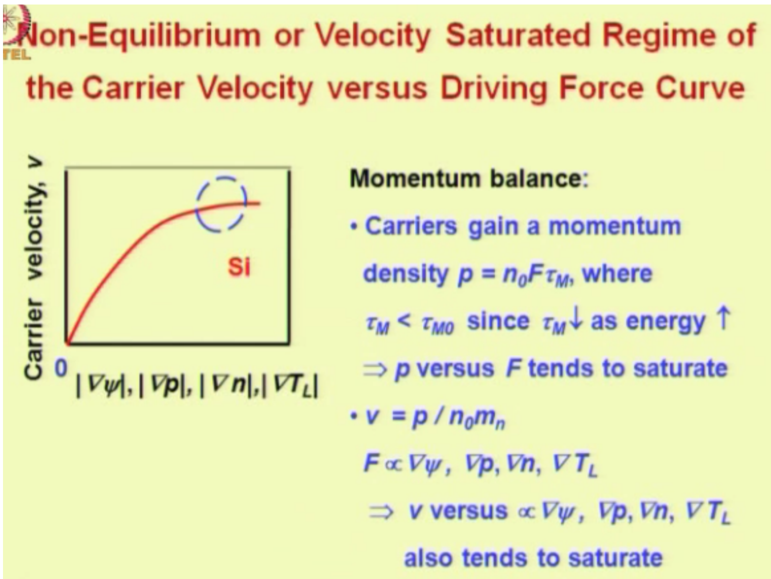

Now you know from the first level course that the density of states increases with energy, if you recall some sort of diagrams like this, this is the conduction band H, this is balance band H and you plot the density of states function like this. So this is energy and this is the density of state function in E. And the number of states in any energy interval DE is given by this, so you can see that more the energy more the number of states.

So in a very simple way we can say that if the carriers have high energy then they have more states into which they can scatter and therefore scattering rate is more, because scattering rate is more the number of scattering event is more in any unit time, then the time associated with each scattering would be lower. So that is why tau M is less as compared to under equilibrium. Now the consequence of this is that P versus F curve tends to saturate.

Because now tau m is now decreasing, as F increases, tau m decreases. So the product F into tau m now is not increasing linearly. It is sublinear. Now again following the equilibrium, arguments here the velocity is given by P divided by n not mn and the force is proportional to these gradients. So putting these 3 things together, the velocity versus the gradients also tend to saturate. Now let us consider the energy balances.

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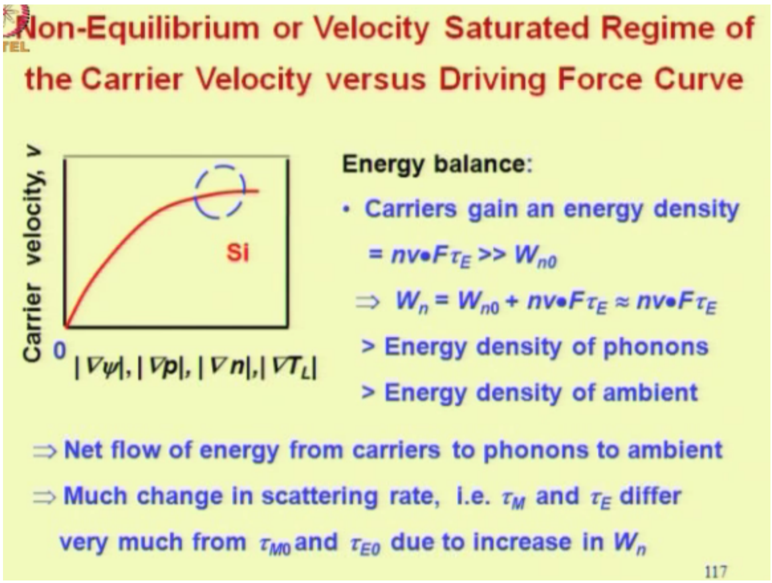

Now the carriers gain an energy density given by nv into F into tau E. There is a dot between E and F here. This dot represents the fact that the velocity and force both of these vectors, we are taking the dot product. In fact, this should have been explained at the time of discussion of the equilibrium case also, because there also we had used a dot product. This dot is really not important if the situation is one dimensional.

Because in that case the product of the vectors is simply the product of the magnitudes. So this energy that is gained from driving forces is much more than the equilibrium kinetic energy density. This is really the statement of non-equilibrium that the energy gained from the driving forces is much more than the equilibrium kinetic energy density. The statement of false equilibrium is that this energy gained from the forces is very, very small compared kinetic energy density under equilibrium.

So converting this into an equation Wn = Wn0+nVF tau E and this sum is approximately = nVF tau E itself. Now this energy therefore will become more than the energy density of phonons. Now this is where the equilibrium has been disturbed and also the energy density of phonons will be more than the energy density of the ambient. So let us understand this fact, right what does it mean?

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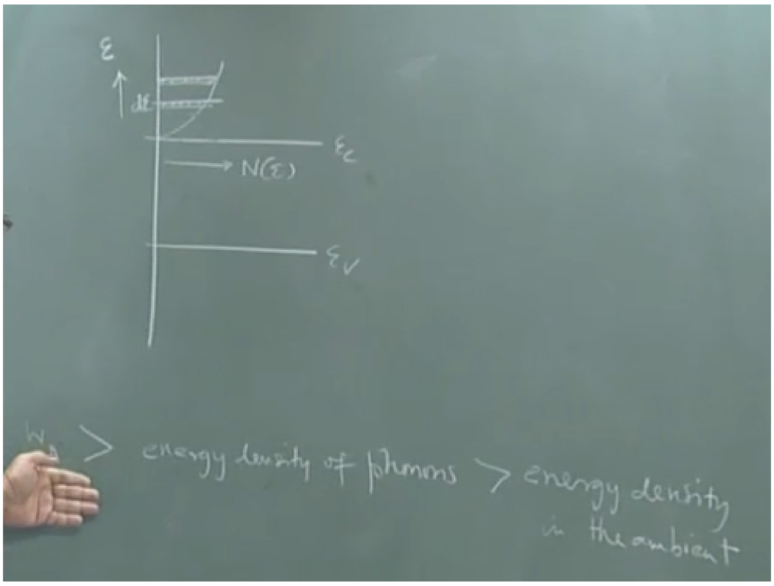

So we are saying that Wn that is the kinetic energy density of electrons is more than energy density of phonons is more than the energy density in the ambient. So there is a net energy transfer. The carriers are gaining the energy directly from the forces. You see the phonons cannot gain energy from the driving forces. Because the driving forces act on the carriers only. Now as the carriers gain energy, since their far exceeds that of phonons and as pointed out here, there is an energy exchange between the various populations.

So whatever we talk between electrons and phonons, also applies between holes and phonons. So we should extend the argument. Now since this energy is increasing as compared to phonons, where there is this energy exchange scattering between them, some energy transfer is taking place and therefore the phonon energy also increases above the equilibrium value.

However, it always remains less than the carrier energy so that there is a differential that allows you to transfer energy from carriers to phonons. So energy transfer is from force to carriers, from carriers to phonons and then from phonons, the energy is transferred out into the ambient. Therefore, the phonon energy is more than the energy density of the ambient. Now this series of energy transfers explains why under non-equilibrium conditions or high driving force conditions, the semiconductor sample gets heated up.

So what is happening is that heating up is really the increase in energy density of phonons as compared to ambient. Because unless this gets heated up compared to the ambient, energy transfer cannot happen from the phonons to the ambient. Now energy of phonons is nothing but energy of lattice vibrations. So that is lattice temperature. So that is how the semi-conductor temperature increases allowing it to transfer energy to the ambient.

Under steady state, this energy transfer should be such that all things should stabilize. Under steady state, the carriers will have a high kinetic energy density as compared to phonons or lattice vibrations and this will have high energy compared to the ambient. So this is in terms of this diagram, the temperature here is more than the ambient temperature, so that there is a series of energy transfers possible.

Under steady state, this energy transfers ensure that the various energy densities stabilize, but always this order will be maintained. Kinetic energy density of carrier is more than energy density of phonons or lattice vibrations, which is more than the ambient energy density. Whatever we said now is captured in the slide. Net flow of energy from carriers to phonons to ambient.

Now as a result of increase in energy density of carriers, another consequence is much change in scattering rate, that is tau m and tau E differ very much from the equilibrium values of tau m0 and tau 0. Now we have already argued how tau m decreases. It turns out that the appropriate scattering mechanisms if these are considered from quantum mechanics, the energy relaxation time can in fact increase with increase in carrier energy.

We will just accept this fact as a result from quantum mechanics.

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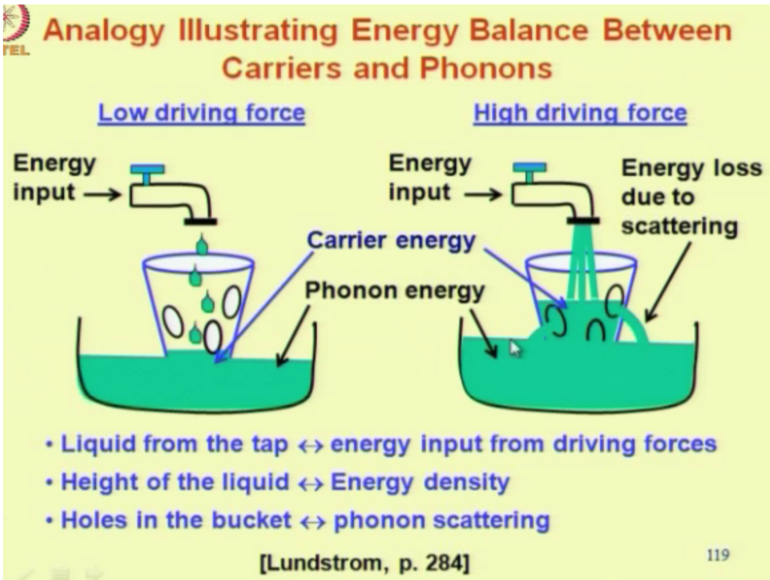

Now let us consider an analogy illustrating the energy balance between carriers and phonons. Since this is a very important topic, we want to make ourselves comfortable with how the energy exchange happens between carriers and phonons. Because scattering of carriers by phonons is responsible for many of the effects. So here we have shown 2 situations, low driving force and high driving force.

The analogy basically involves filling a tub consisting of a can with holes with water from a tap. So the water input into the tap is like the energy input and this water when it falls into the can, what happens is that through the holes in the can, it gets into the bucket or the container. Now, when the driving force is small, it is equivalent to small energy input or you open the tap very little, so that the water is falling very slowly.

So what you will find is through the holes, the water will quickly get into the larger bucket and therefore the water level inside the can and inside the remaining part of the bucket would almost be the same. So you see the water level here is only slightly higher than the water level outside. Now as against this, if the rate of energy input is large, that is if you open the tap very much.

The water is coming out at a very fast rate and so water level in the can is much higher than that in the bucket. No doubt, the water is coming out of the holes, but it cannot come out at that very rapid pace unless the water level in the can rises. Because once the water level in the can rises, then there are more holes available, through which the water can flow out. So the carrier energy is represented by the water in the can.

Whereas the phonon energy is represented by the water outside the can in the bucket and these holes represent the opportunities for loss of energy or scattering and water flowing out represents the energy loss due to scattering. So this is summarized here. The liquid from the tap is analogous to the energy input from driving forces. The height of the liquid is analogous to the energy density and holes in the bucket is analogous to phonon scattering.

So this explains why the carrier energy is higher than the phonon energy when the driving forces are high or the energy input is large and the difference between the 2 levels will be more when the energy input is more. In fact, one can very loosely associate temperature with the height of the water level. Now to help you understand whether you have got the analogy illustrating the energy balance between carriers and phonons, here is an assignment for you.

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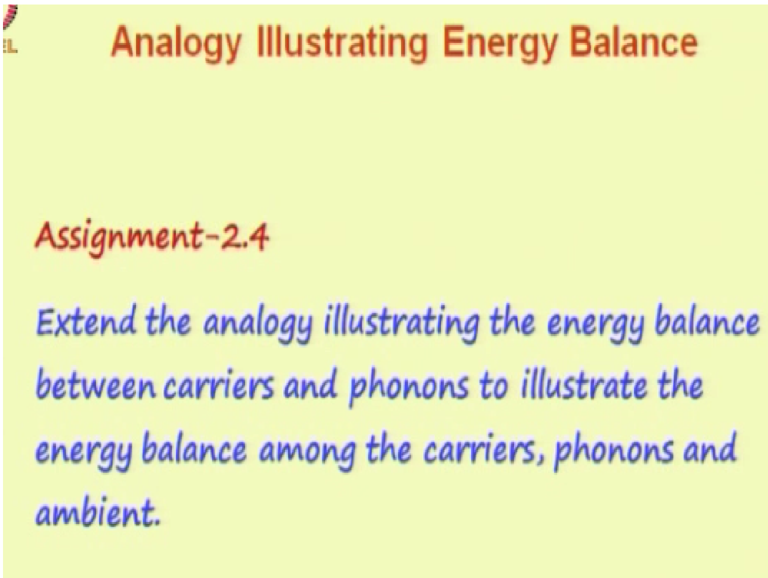

Extend the analogy illustrating the energy balance between carriers and phonons to illustrate the energy balance among the carriers, phonons and ambient. So I want you to add ambient to the picture. So you have to show how water from the tap gets transferred from the can with the holes to the larger bucket and from the bucket to the ambient.

We will now introduce an important concept namely that of carrier temperature. This concept of carrier temperature is analogous to the concept of lattice temperature, which all of us are familiar with. So in fact whenever we talk of temperature of a solid, we are talking of actually the lattice temperature. When I touch an object and I say that it is hot, it means the lattice temperature of the object is more than the ambient temperature or my body temperature.

Now, what is the concept of lattice temperature. Let us review it briefly. At any temperature > 0K, all the atoms of the lattice or semiconductor or solid are in random thermal vibration. Now the index of the energy associated with these vibrations is the temperature. So when the energy is large, the temperature is large. So just as we associate lattice temperature with lattice energy or lattice vibrations, we associate carrier temperature with the kinetic energy of the carriers.

So carriers are in random thermal motion and they may also have a directed motion superimposed over the random motion. Now this energy, because of this kind of motion, can be associated with the temperature. That is what we would not like to do, because this concept of temperature can then be very useful as we will see with some examples. The picture is as follows:

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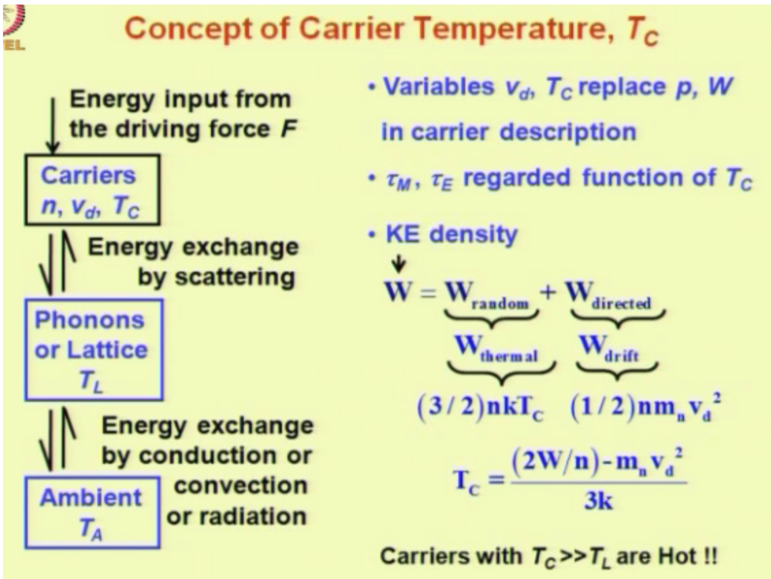

So this picture is about the energy exchange. So driving force provides energy to the carriers. Now the carriers are described in terms of 3 variables namely the carrier concentration, the drift velocity and carrier temperature. In the concept of carrier temperature, this is the way we describe the carriers. Now notice that the parameter n is the carrier concentration or carrier density. The parameter Vd drift velocity is actually nothing but the momentum in a different form.

And similarly the carrier temperature is the energy of the carrier. So really these 3 parameters represent the carrier concentration, the momentum density and the kinetic energy density. Now there is an energy exchange between carriers and phonons or lattice and that is shown by this arrows here. This energy exchange happens by scattering, so they collide with each other. Then there is an energy exchange from the lattice to the ambient.

This energy exchange can happen by conduction, convection or radiation. So we have a temperature for the lattice and similarly to represent the energy density in the ambient, we have the concept of ambient temperature. We are already very familiar with the lattice temperature and ambient temperature ideas. So it should not be difficult to extend our understanding to the concept of carrier temperature.

So the variables Vd, Tc replace momentum density and energy density in the carrier description and now momentum relaxation time tau m and energy relaxation time tau E can be regarded as functions of carrier temperature. So their functions of carrier energy, now we are seeing their functions of carrier temperature. Let us write in equation for the carrier temperature.

The kinetic energy density represented by W can be separated into 2 parts, the random component and directed component. Now this is very crucial to the concept of carrier temperature. The carriers are all moving randomly and there is a directed motion superimposed over random motion because of some driving force. What we are doing is, we are separating the energy associated with the random motion and associated with directed motion.

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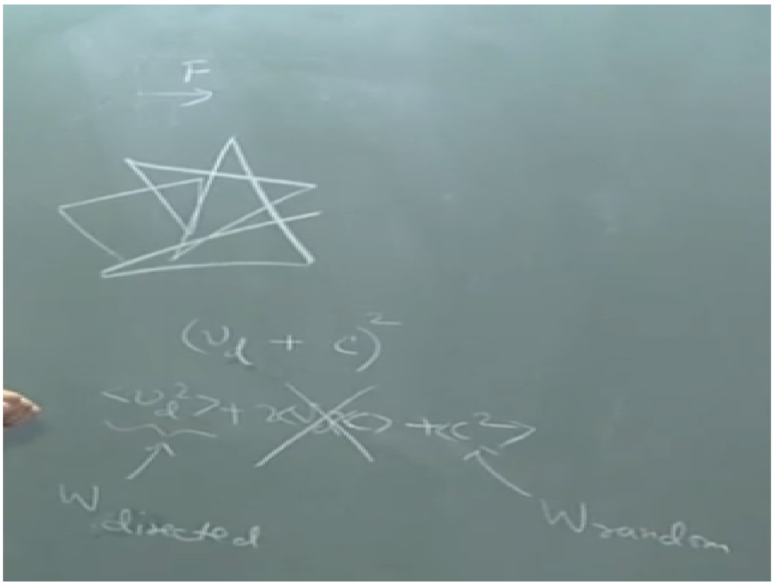

How can you do that? Well, if you consider the velocities, namely the drift velocity and the random velocity and say that the velocity of a carrier is separated into 2 parts and if you square this, you will get the terms Vd square +2Vdc+C square. Now, when you average this for all carriers as represented by these arrows, then the average of the random component is 0, therefore this term goes away.

The average of square of the random component, however is non-zero. This will give rise to the root mean square average. Similarly, the average of the directed component square is also non-zero. So really, this is what represents the W drift or W directed and this is what represents the W random. There are more details of this derivation, which are beyond the scope of our course, but this explains to you how I can separate the energy component into 2 parts.

So this separation is also talked about in terms of thermal energy and drift energy, directed energy is also called drift energy, random energy is also called thermal energy. Now one clarification, the word drift here should not be associated with the drift current alone. So the word drift is really meaning the directed energy. So it can be because of diffusion or because of thermal electric current also in this nomenclature for energy.

Now it is the random component that we convert to temperature. So since this is energy density, you have the electron density coming here, otherwise except for this term n, it is a familiar equation, 3/2 times Boltzmann constant into the carrier temperature. Now you know that the average energy of a phonon is written 3/2 times the Boltzmann constant into lattice temperature.

Similarly, the average random energy of a carrier is written as 3/2 times K into carrier temperature. Now because we are talking of kinetic energy density, the electron concentration is coming in there. So it is to be emphasized that only the random component of the energy can be associated with the temperature. Directed component has to be separated out. Even in the case of lattice temperature, it is a random thermal vibration, which contribute to the temperature.

Now writing for the drift energy half of M into V square, drift velocity square and then multiply by electron concentration because it is energy density. Now you can transform this equation, W = 3/2 times nKTc+ half of nMn Vd square. To write the expression for carrier temperature as 2 times W/n-MnVd square by 3 times K. So this is how you can calculate the carrier temperature for any kinetic energy situation, after separating out the directed energy.

So in this context of carrier temperature, that people talk about the hot carriers. So hot carriers are really carriers whose temperature is much larger than lattice temperature. So in principle, when the carrier temperature is more than lattice temperature, they are hot, however only when the difference is large, we really call the carriers hot, just in the same way as, if I touch an object, which is at say 30 degree centigrade, it would not appear much hot.

We do not say the object is hot. Because room temperature is about 25 degree centigrade, but when it is 70 degree centigrade or something like that and when we touch, we really feel the heat, then we say the object is hot. In a similar way, when the carrier temperature is much larger than lattice temperature, then we say the carriers are hot. So that is the concept of hot carriers. Please do not misunderstand hot carriers as carriers in a hot semiconductor, no.

The lattice temperature may be equal to the ambient temperature, but carrier temperature can exceed the lattice temperature. So hot carriers are carriers with high kinetic energy in maybe a cold lattice.

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So we have come to the end of the lecture. So let us make a summary of the important points. So in this lecture, we talked about carrier, momentum and energy densities of carriers and we said how we can analyze carrier motion in terms of the balances of carrier, momentum and energy densities. So first, we explained that what is the meaning of these carrier balances under equilibrium.

Then we showed how based on momentum balance considerations alone, one can explain the various forms of carrier transport, namely the drift, the diffusion and the thermal electric current. Then we took up the carrier velocity versus driving force curve and we separately explained the low driving force or quasi-equilibrium region, which is also called the ohmic region and the non-equilibrium are high driving force or velocity saturated region.

So for these 2 conditions, we led out the statements of carrier balance, momentum balance and energy balance and we explained how the whole shape of the curve arises and can be understood in terms of these balances. Since the energy exchange between carriers and phonons is a very important phenomenon, based on which many effects can be explained, we gave an analogy to illustrate how the energy balance between carrier population and phonon population is coming about.

Finally, we introduced the concept of carrier temperature in which we said that the random energy associated with the carriers can be expressed in terms of an equivalent temperature in much the same way as the random vibrations of the lattice, the energy associated with these vibrations can be expressed in terms of a lattice temperature and the energy density in the ambient can be expressed in terms of the ambient temperature.