Semiconductor Device Modeling
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Lecture – 03
Semi-classical Bulk Transport: Qualitative Model

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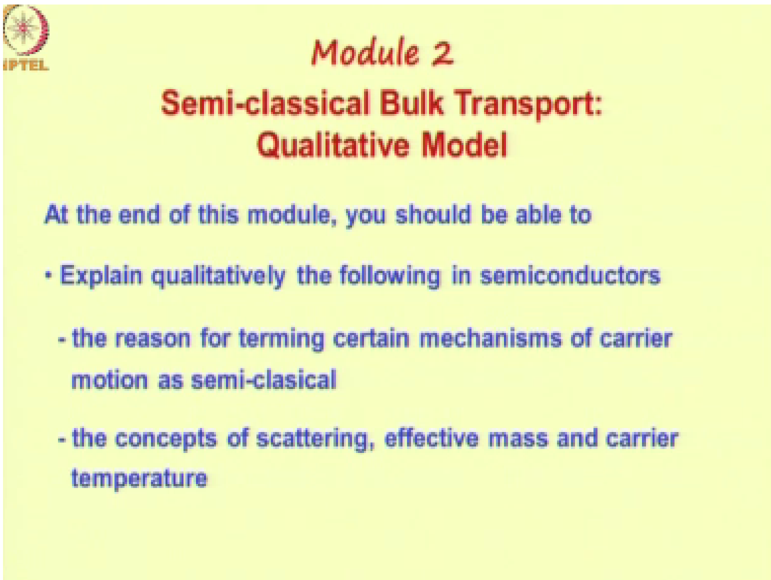

So, let us begin our discussion on the semi classical bulk transport. We begin with the qualitative model of semi classical bulk transport. So, at the end of this module, you should be able to explain qualitatively the following in semiconductors. The first reason for terming certain mechanisms of carrier motion as semi classical. Next, you should be able to explain the concepts of scattering, effective mass and carrier temperature.

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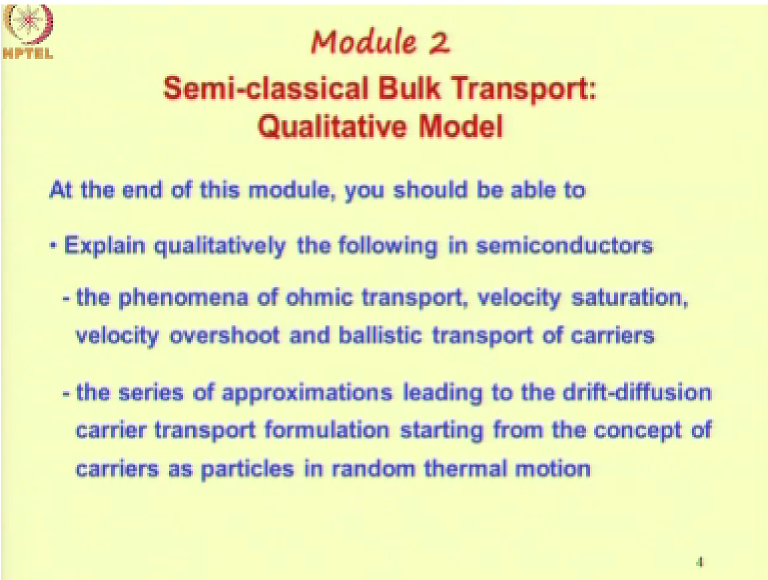

Then, you should be able to explain the phenomena of ohmic transport, velocity saturation, velocity overshoot and ballistic transport of carriers. You should be able to explain the series of approximations leading to the drift diffusion, carrier transport formulation starting from the concept of carriers as particles in random thermal motion. We will first point out; what are the mechanisms we would like to explain?

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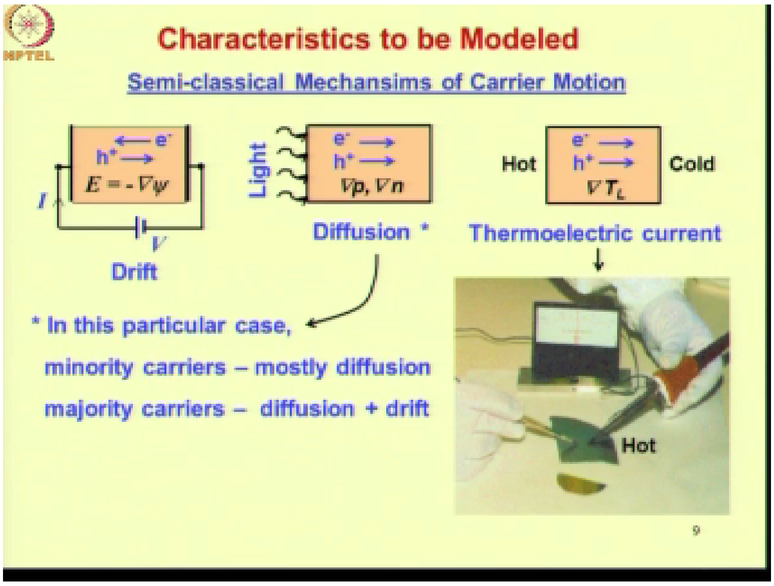

Now in this slide, we are showing the drift transport. You can see that a voltage has been applied to a uniform semiconductor bar and a field has been set up, which is equal to negative gradient of psi; psi is a potential. As a result, the electrons are moving from right to left and the holes are moving from left to right. So, you see that in drift transport, the electrons and holes move in opposite directions.

The next mechanism of transport is diffusion, so this slide shows the situation where diffusion current is set up. So, you have light falling on the left end of a semiconductor sample and that is generating excess electron hole pairs in a thin region near the left surface, where the light is falling. Consequently, the electron and hole concentrations are raised at the surface as compared to the bulk.

So, what you find is; both electrons and holes are moving to the right because of the concentration gradients of holes and electrons, shown as gradient of p and gradient of n. So, because gradient of and gradient of n is created in the sample by illumination of the left surface, electron and hole diffusion currents are maintained. Now, there is one clarification, so I show in the slide; in this particular case, while the minority carriers flow mostly because of diffusion, the majority carriers flow because of diffusion as well as drift.

Now, this is because in this case, the electrons and holes are both moving to the right, since there is no current injected from the left end, together the electron and whole current should add up to 0, but diffusion coefficient of electrons is more than that of holes and therefore the electron into diffuse faster than the holes. So, the only way you can bring that electron and holes currents in step is to have an electric filed created, which will oppose electron motion and aid the hole motion.

So, this electric field has a strong impact on the majority carriers and therefore the majority carrier current is because of diffusion as well as drift, whereas minority carrier current is because of diffusion alone. So, this clarification is important because we should not think both majority and minority carriers are moving by diffusion alone. In the first level course, we have discussed the detailed analysis of this situation.

Explaining; how the field arises, how it affects the majority carriers and how it does not affect the minority carriers that much. Let us look at the third mechanism of transport namely the thermoelectric current. So, here the left end sample or the left end of the sample has been made hot, a temperature has been increased as compared to the right end, which is cold. So, the current is set up because of a temperature gradient.

So, that is why the gradient of Tl is shown there; l stands for lattice or semiconductor; semiconductor atoms. So, later on we will distinguish between what is called lattice temperature and carrier temperature. For now, let us just refer to the situation in terms of one temperature namely the lattice temperature. So, once there is a temperature gradient the slide shows that there is a flow of carriers from the hot end to the cold end.

So, the both electrons and holes flow from the hot end to the cold end. An example of thermo electric current in practice, so what I shown here on the slide is a semiconductor sample on which a soldering iron has been positioned and this soldering iron is hot. So, this hot soldering iron adds us one contact namely the hot contact and you have another contact which is a simple probe, which is at room temperature just on the side, on the left hand side.

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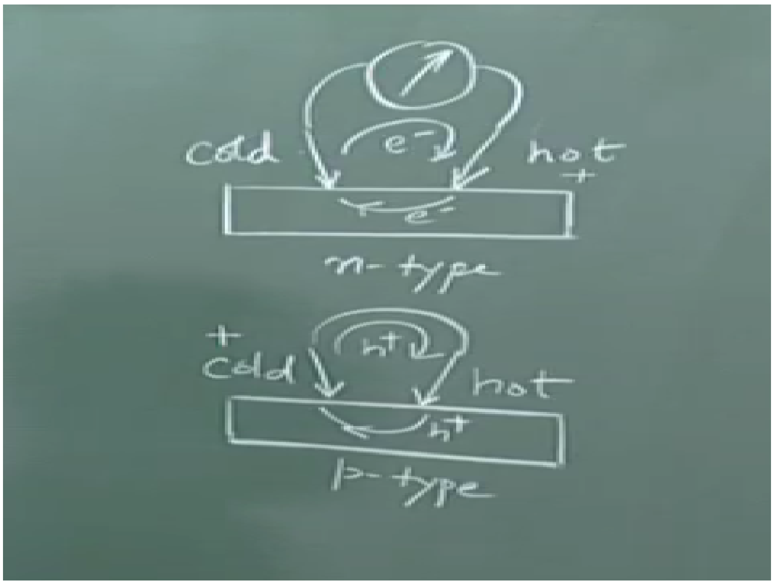

So, now a current flows from the hot end to the cold end; from the soldering iron to the other probe within the semiconductor and if the circuit is closed using galvanometer, I shown here, then the galvanometer will detect current. So, it is something like this. So, this is the semiconductor, this end is hot and this end is cold, this is using the soldering iron and then you are connecting a galvanometer here.

Now, inside you will have both electrons and holes moving from hot end to the cold end. Let us assume that this is an n type sample. Then the electron current will dominate because number of electrons is large. So, when the circuit is completed outside also the electrons move like this, so which means the hot end is positive and the cold end is negative. So, the conventional current will flow from the hot end to the cold end; outside the semiconductor.

Now, by looking at the polarity of the current, we can figure out the polarity of the sample. So, look at this again here, now if the sample was p type, then in the same situation you would have flow of holes here, flow of electrons would be there but you know the electron concentration is small, so the hole flow will dominate and the same holes, when you close the circuit, the same holes would move in this direction.

Now, in this case therefore the cold end would be positive, so if the hot end is positive, then you know it is an n type sample, if the cold end is positive, it is a p type sample. So, thermoelectric current is used for detecting the polarity of the semiconductor sample. So, we will explain these 3 mechanisms of carrier motion. So, when you look at the slide, all the 3 mechanisms are shown side by side, so drift is because of potential gradient; grad psi.

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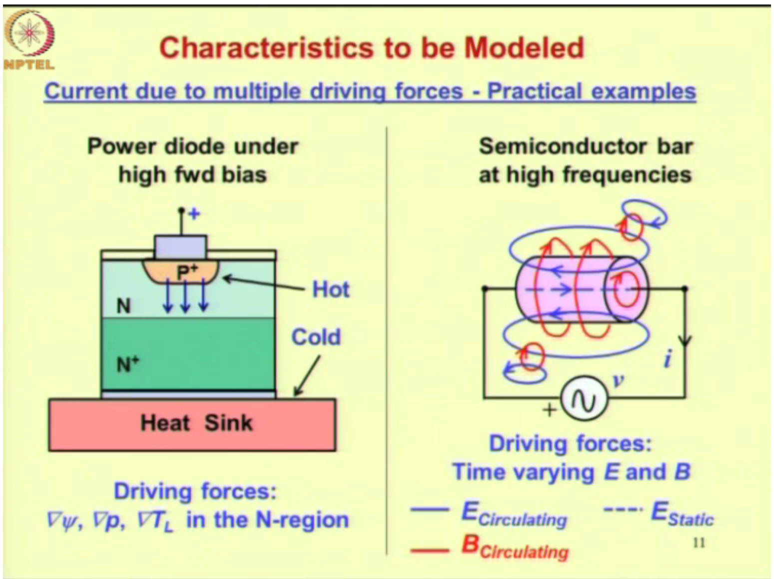

Diffusion is because of concentration gradient, gradient of p or gradient of n and thermoelectric current is because of temperature gradient; gradient of Tl. The next slide shows some practical examples; you see in practice drift diffusion and thermo electric currents can all be present together. So, different mechanisms of current flow can happen together. So, this is what we want to illustrate here; how the mechanisms occur together?

And how the situation is much more complex than what we have depicted, where we construct 1 mechanism at a time. The example on the slide here is power diode under high forward bias. So, here you can see that a current is flowing from the p+ region into the end region, I shown by these arrows. Now, you know from the basic diode theory discussed in the first level course, that most of the voltage drop occurs across the depletion layer.

So, the depletion layer, the region near the junction is a place where the power will be dissipated, right. So, heat will be generated at that location and that is why on the slide this region is shown as hot, on the other hand, there will be a heat sink connecting to the diode to cool the diode and the heat sink will be at room temperature. So this cold, so you see there is a heat flow from the junction towards the heat sink or there is a temperature gradient, right.

So, this temperature gradient would set up a thermo electric current. Now, from basic diode theory, you already know that there is a diffusion current in a diode because excess carriers are injected; for instance, the p region injects holes and so, there is a hole diffusion current in the end region away from the junction. Now if the injection level is high, then you know that in addition to drift; in addition to diffusion, there would also be drift current.

So, in regions where there is an electric field, you would have drift current, so this is an example of a situation where drift diffusion and thermoelectric current are all present. Generally, in power devices where you are dissipating large amounts of power, these 3 currents will be present together. Let us take another example shown on the; here what we are showing is semiconductor bar at high frequencies.

So, we consider a cylindrical semiconductor bar, which is uniformly doped; something that would appear like a resistor at very low frequencies, right. So, high frequencies, the analysis of this would be a little bit involved because you will have to consider both electric and magnetic fields and also you will take into account the time bearing nature of these fields because you are applying an alternating signal.

So, let us look at this slide here, a number of arrows are shown. The dashed arrow here shows the electric field because of charges, so at an instant when the left end is positive, I shown by the positive sign here, you will have an electric field because of static charges from left to right. So, this is what this arrow shows. Now, when the frequency is low around this electric field; around the semiconductor bar, which is carrying current, you will have a circulating magnetic field, so that is shown by this red arrow here.

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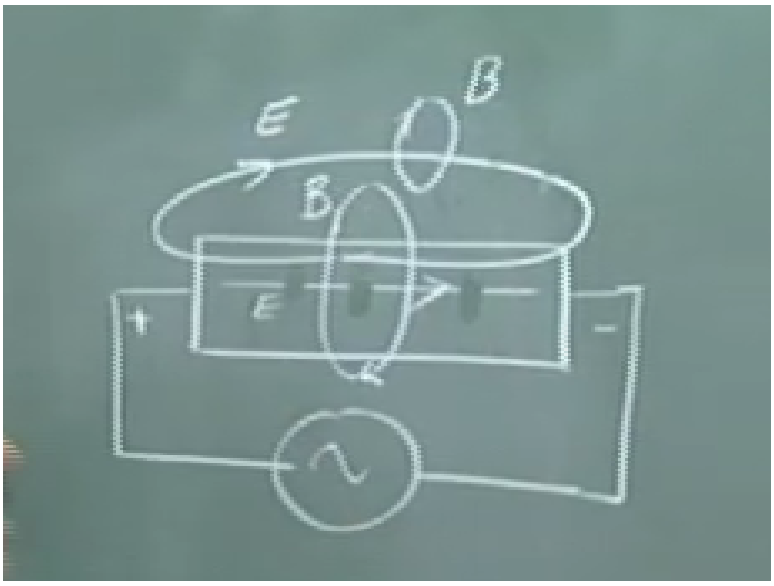

So, when the frequency is low, the picture is something like this. So, assume this end is positive and this end is negative, you have a current flowing like this, then this current sets up a magnetic field; so which is like this. So, at low frequencies these all what you have, this is the electric field shown by dotted line in this slide and this is the magnetic field plus you raise the frequency; what happens is; around the changing magnetic field, a changing electric field is set up.

So, that is shown by in fact circulating arrows like this. So, this is changing electric field E. So, against this field, which is an electric field because of static charges; positive charge at the left end and negative charge at the right end, this is circulating electric filed. You know from your course on electromagnetic fields that around circulating magnetic fields, if the magnetic field is changing with time and this rate of change is large, a circulating electric field is created.

Now, a circulating electric field in turn will also have around a circulating magnetic field, right. So, this is our electromagnetic wave emanates at high frequencies. So, this is what is shown here in the diagram. So, there are number of arrows; this is what this arrow show. So, what you are saying is; even a simple semiconductor bar when the frequency is high, you will have to consider electric and magnetic fields and the time bearing nature of this fields.

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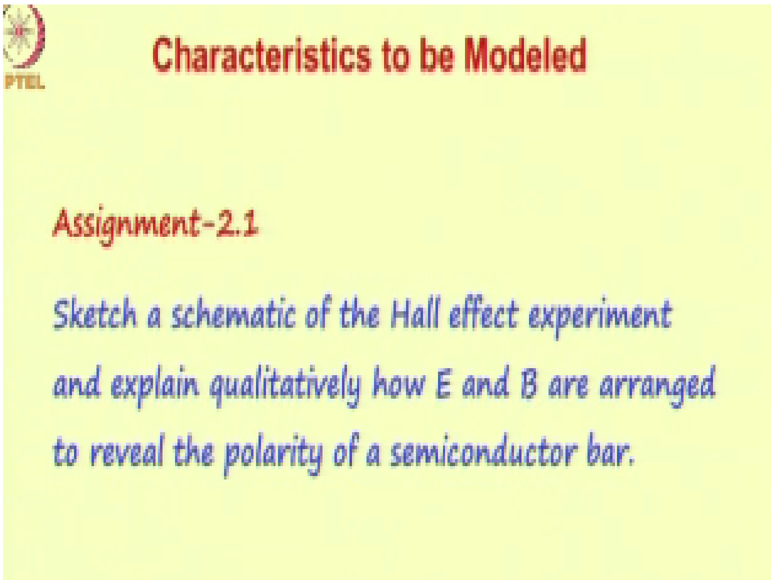

Now, here is an assignment for you; sketch the schematic of the Hall effect experiment and explain qualitatively how E and B are arranged to reveal the polarity of a semiconductor bar. So, here E means electric field and B means magnetic field.

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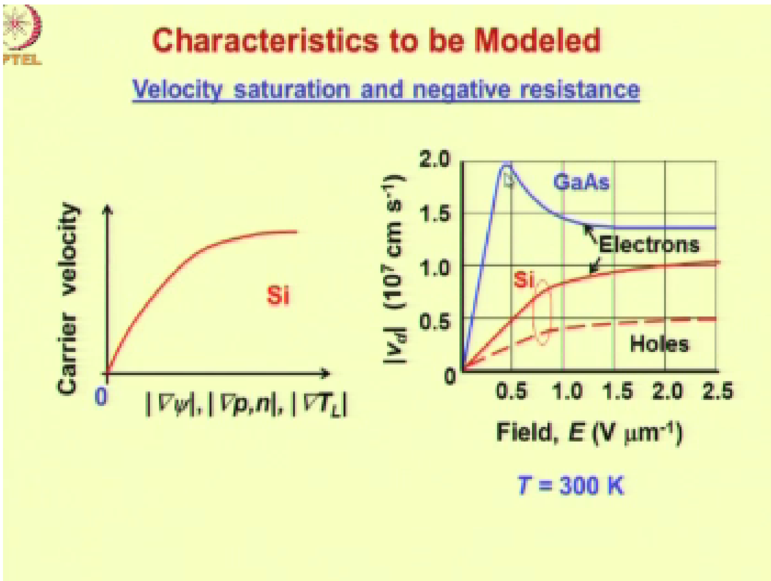

Let us look at other characteristics, which we would like to explain; here we are talking of velocity saturation and negative resistance, so first let us look at velocity saturation. The slide shows, the carrier velocity in response to gradient in either potential or concentration or temperature. So, here p, n means; this is gradient p, gradient n. What the slide shows is that the current rises linearly when the gradients are small or driving forces are small.

But, when the driving force is large, the current saturates. So, this is called velocity saturation. The velocity saturates or the current saturates. Now, we show on the slide some quantitative figures. So, here the slide shows the velocity verses field characteristics that means actually current verses voltage, so you are applying a voltage across a uniform semiconductor bar and you are sleeping the electric field.

Or you are encouraging the voltage and as a result, the velocity undergoes changes. Now, concentrate on the slide, we have shown here the velocity field characteristics for silicon and Gallium arsenide. For silicon, we have shown the curve for electrons as well as holes. For Gallium arsenide, we have shown it only for electrons. If you can see the curve for silicon, the velocity increases linearly in the beginning and then saturates.

So, you see the electric field range is from 0 to about 2.5 volts/ micron and velocity saturation occurs beyond about 1 to 1.5 volts/ micron. Now, mobility of electrons is less than that of holes, therefore a mobility of electrons is more than that of holes therefore the electron curve is above the hole curve and now when you come to Gallium arsenide, what you find is the velocity increases linearly for small electric fields but it over showed the saturation velocity.

And then for larger electric field, there is a region where the velocity decreases with electric field and then the velocity saturates. So, this region where the velocity decreases the electric field is called a negative resistance region because this means that the current is decreasing with voltage. So, we would like to explain the velocity saturation behaviour in detail and we will explain very briefly how the negative resistance region raises.

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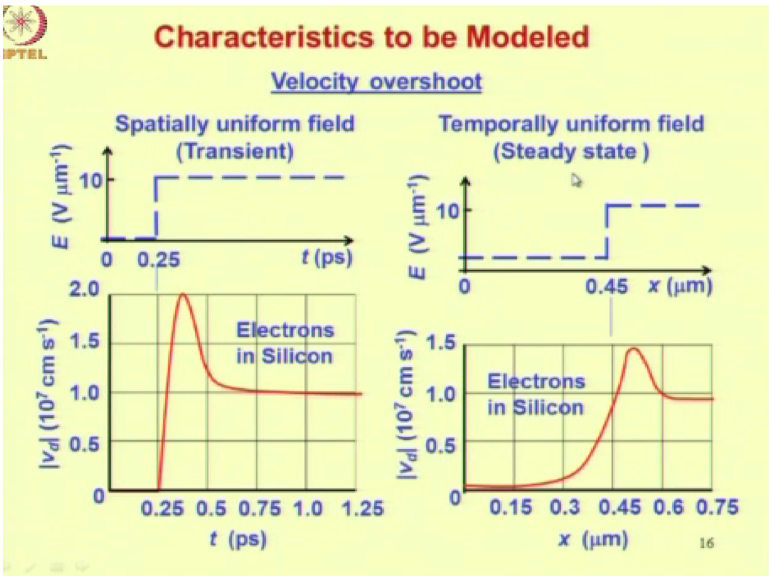

The next slide shows velocity overshoot characteristics. Suppose, you step the electric field suddenly at some instant of time and the electric field step is large. For example, here, the electric field step is about 10 volts/micron, what would be the response of the carriers inside the semiconductor. So, here the slide shows the response of the electrons, so electron velocity.

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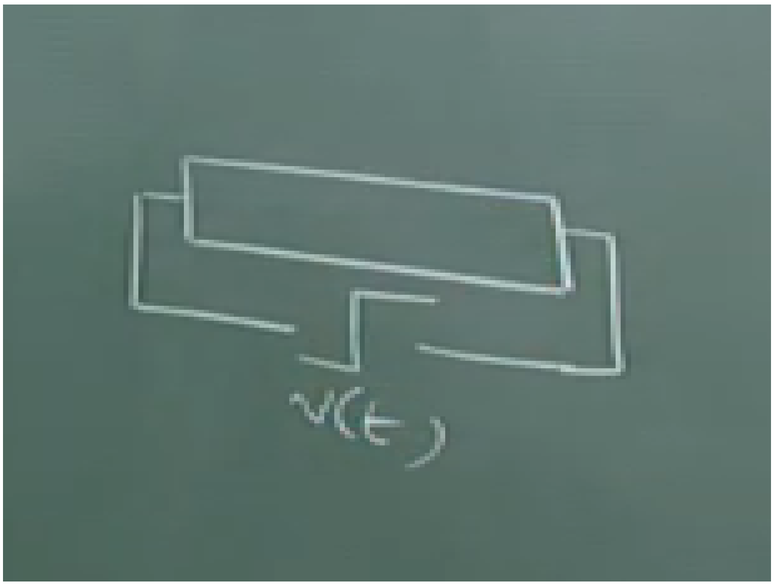

So, what you find is the velocity increases linearly with time and then it overshoots the saturated velocity or saturation velocity. So, there is a region where the velocity decreases with time and then it saturates. So, we would like to explain how this hole curve arises. So, this is the situation something like this, so you are taking a uniform semiconductor and you are suddenly stepping the voltage as a result of which the electric field is also step.

So, the semiconductor bar is uniform. Now, the velocity is changing with time but always at any instant the velocity remains uniform over the length. So, this is important to appreciate. Now, this would show here on the slide, you can see that, we have said this velocity spatially uniform or the field is spatially uniform and as a result the velocity is also is spatially uniform. But it changes with time, it is a transient situation.

Now, as against this, the slide shows also another type of velocity overshoot, which comes if you step the electric field at some location within the semiconductor. So, I shown in this slide again you are applying a large field step, however here it is at some location in the semiconductor. So, you have a low field over some region of the semiconductor and then the suddenly field changes with high value.

How we can apply such electric fields or we can bring about such a step is not the question that we would like to answer at this point, we would just want to see; suppose such a step is there in the electric field, how will the velocity respond? Now, below is shown the velocity curve as a function of distance so what you find? Is the velocity increases from a low valve corresponding to the low electric field, near the step it starts increasing and it overshoots the ultimate saturation value.

Then, the velocity comes down and saturates, so the difference between this velocity overshoot and the velocity overshoot corresponding to a transient situation where you suddenly step the electric field at some instant of time, is that while in the spatially uniform field case or transient situation, the velocity started increasing after the electric field change in time. The spatial velocity overshoot here seems to indicate that before the field step occurs the velocity starts increasing.

Now, it is important to note it does not mean non causality because it is not other function of time, but as a function of distance. So, the velocity is starts increasing before the location of the electric field step and then it increases an overshoots and then returns to the saturation velocity value. So, we would like to explain these entire velocity overshoot characteristics. Now, this is the situation of temporarily uniform field that is the field is uniform as a function of time.

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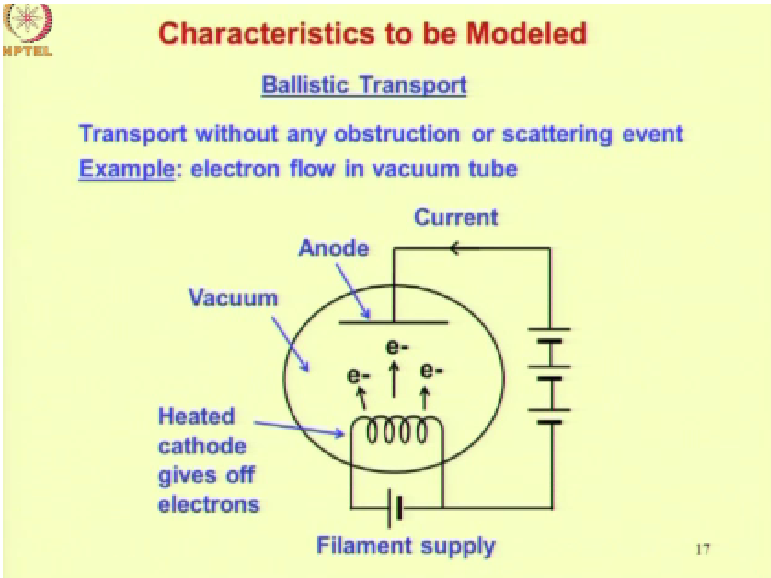

So, this is the steady state situation, so the previous situation that we discuss what transient; on the left hand side, you have the transient velocity overshoot on the right hand side, you have velocity overshoot as a function of distance in a steady state situation. Let us look at the next slide; here we are talking of Ballistic transport. The slide shows not a semiconductor but a vacuum tube.

The Ballistic transport can be very well understood with the example of a vacuum tube and later on we can see how such a situation can arise in a semiconductor as well. So, what is Ballistic transport? As a slide says it is a transport without any obstruction or scattering event. Now, you know that in semiconductors, the electrons encountered lot of pollutions from lattice atoms, vibrating lattice atoms, impurity atoms and other carriers, okay.

Now, as against that situation in a vacuum tube what is shown here is the electron motion from the heated cathode to the anode occurs without any obstructions. So, you can see the electron is moving from the filament to the anode but it is not getting scattered by anything because this is vacuum you do not have any impurity atoms, do not have vibrating lattice atoms nor or the carriers trying to hit each other, okay.

So, this is an example of a Ballistic transport like a bullet, shot from the filament, the electrons move to the anode without any obstruction. Now, this kind of situation can arise in a semiconductor, if the semiconductor region between the 2 contacts is very thin particularly if it is much less than what is called the mean free path of electrons between any 2 collisions. In such a case, for one contact to other contact, the carriers may move because of Ballistic transport.

So, let us summarise the characteristics that we want to explain. First, we want to explain how current can be created by either a potential gradient or a concentration gradient of carriers or a gradient of temperature, then we want to explain how for high driving forces, the carrier velocity ends to saturate and in some situations, some semiconductors like Gallium arsenide, before the velocity saturates, you have a velocity region of operation in which the velocity decreases with increase in voltage that is called the negative resistances.

Then, we want to explain the response of electrons or holes, the velocity of the carrier when there is a sudden change in the electric field either as a function of time or as a function of distance. So, we will find that the velocity increases to a value that is more than the saturation value and then it returns to the saturation value. Finally, we will construct the Ballistic transport.

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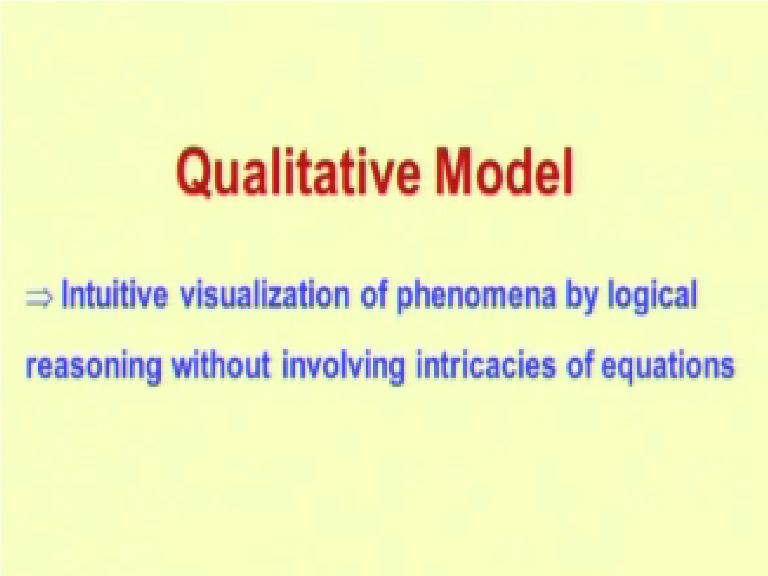

Now, as we had mentioned in the introduction any model that we want to develop should begin with a qualitative part that is; we develop the reasoning for the phenomenon based only on reasoning rather than based on any intricacies of equations. So, that is the first part or model development for all these transport phenomena. As a slide says the qualitative model means intuitive visualisation of phenomena, by logical reasoning without involving intricacies of equations.

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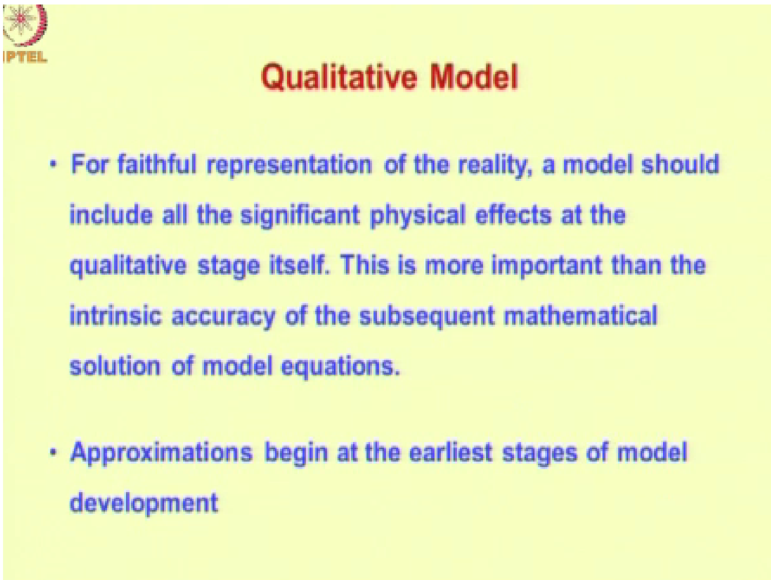

A few points, about the qualitative model that we are going to discuss. So, we are going to follow the following sequence. We discuss qualitative models for equilibrium conditions followed by charge transport in the bulk of a large semiconductor. So, we first we consider the equilibrium situation then will disrupt the equilibrium by bringing in driving forces and then discuss charge transport.

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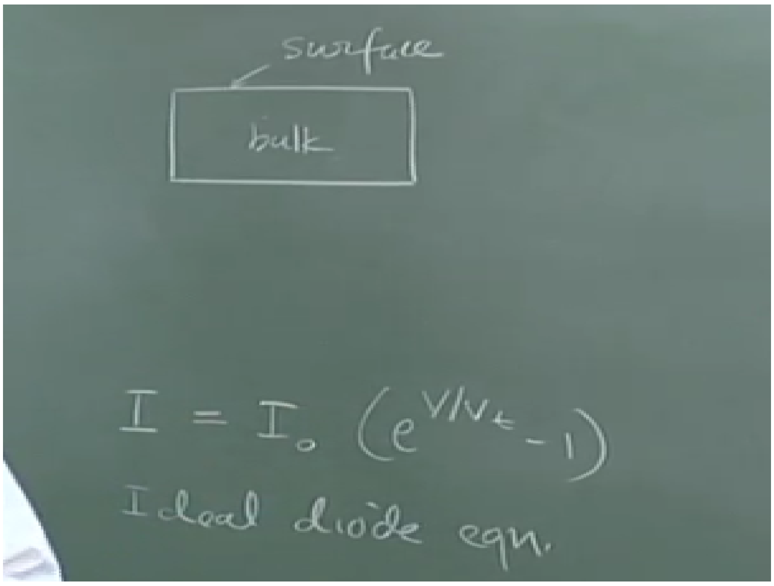

Now, the important thing is that we are going to do this for the bulk region of a large semiconductor. So, suppose this is our semiconductor, then we can identify 2 regions clearly, this is bulk and this is surface. So, what we are saying is we are going to be in this region away from the surface and it is the; this region that we are going to construct the transport. Further, the semiconductor sample itself will be sufficiently large.

Now, what is the meaning of largeness? We will understand at the end of our qualitative model, right now let me just say that it is large enough, so that the carriers undergo several 1000s of collisions, okay within that region. So, it should be large; much larger than the mean free path of the carriers. An important about qualitative modelling is that for faithful representation of reality, a model should include all the significant physical effects at the qualitative stage itself.

This is more important than the intrinsic accuracy of the subsequent mathematical solution of model equation. Now, this point is important because often it is likely that we will consider the accuracy of the model to depend on the accuracy of the numerical calculation. For example, supposing I am considering the diode characteristics, if I use the equation; I = I0 exponential v/vt–1; this is the ideal diode equation.

Now, I suppose use this model and try to predict the characteristics of real diode. Now, one thing I could do is; I can use the calculator that gives me Ballistic 2nd 3rd 4th 5th decimal places, right. Now, would that give me an accurate result? No, because this is an ideal model, does not take into account all the effects. For example, it does not take into account series resistance effect.

Similarly, there are other phenomena, which it does not take into account which are present in a real diode. So, what we are saying is; instead of using a simple model like this and trying to solve it accurately to get more accuracy, what we should do is; to get accurate results, you must incorporate as many phenomena as possible in the equations, okay, in this equation; so as many phenomena as possible, which occur in a real diode in the equation, then that model is accurate.

Finally, approximations begin at the earlier stages of model development. So, the model development starts with the approximations, so you must make intelligent approximations, right from the beginning otherwise we cannot analyse a complicated situation. So, these important points about qualitative modelling, we are going to bear in mind, when we develop the model for the semi classical transport mechanism.

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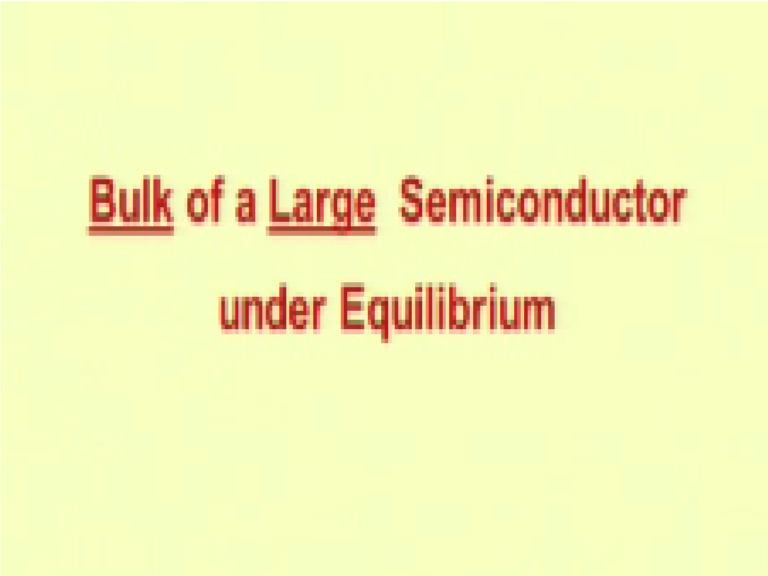

So, we begin with the analysis or model of a large semiconductor bulk under equilibrium.

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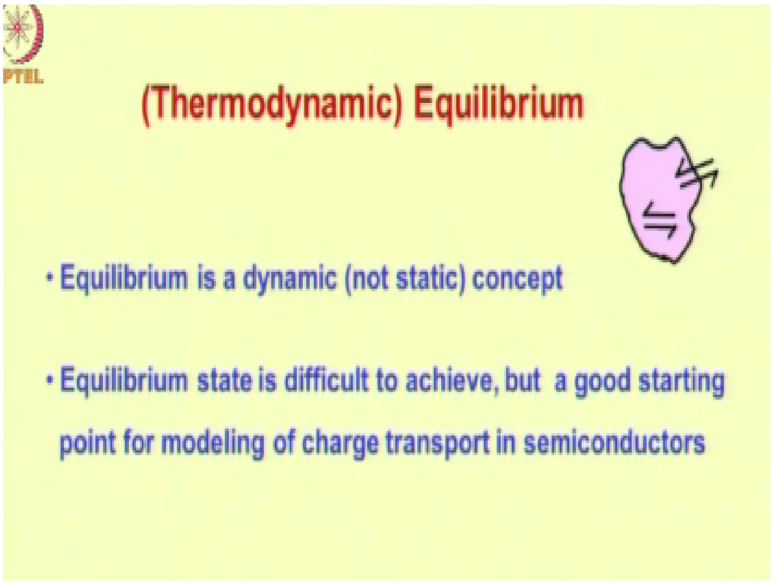

Let us start with the definition of thermodynamic equilibrium. This topic has been discussed in detail in the first level course on solid state devices, which is already available on YouTube. So, you can refer to that discussion, here I am just going to summarise the important points. So, what is the thermo dynamic equilibrium or equilibrium? It is a state, in which the principle of detailed balance holds implying every process in the system is balanced by an inverse process going on at the same rate.

Now, this definition is pictorially depicted here, the diagram shown on the slide. The arrows here indicate the inverse process is going on, so for every process, so arrow in 1 direction, you have arrow in the opposite direction. So, this shows the balance between 2 processes going on at the same rate. Now, this process could be between the semiconductor and the environment or within the semiconductor itself from 1 point to another point.

So, this pictorial depiction is useful because it helps us to remember the definition words. Often the picture remains longer in memory than the words. So, if you remember this picture then you will remember the definition of equilibrium. Now, the definition; that for every process there is an inverse process going on at the same rate. Sometimes looks abstract, so let us make it little bit more practical or concrete.

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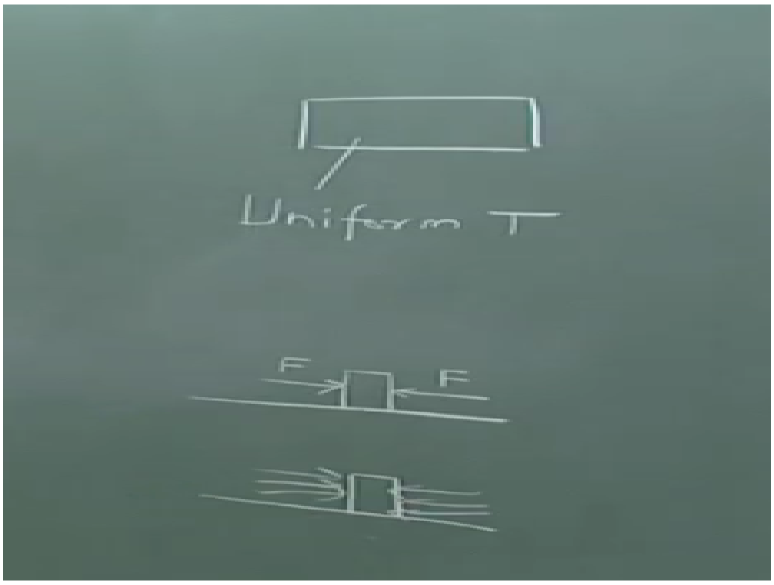

In more practical terms, equilibrium is a state in which there is no excitation other than temperature and no net flow of charge or energy. So, no excitation other than temperature, so this means supposing these are semiconductor, if I am talking about equilibrium state of this semiconductor, then there is no electric field applied, no magnetic field applied, okay. The only thing that we are applying is a heat source.

Further the heat source should not be such that it creates temperature gradient. So, the temperature has to be uniform, why? Because if it is non uniform, suppose in temperature at this point is more than temperature at this point then there is going to be thermoelectric current, you know that and that is why the temperature includes the remaining conditions also that is sample should be at uniform temperature, there should be no net flow of charge or energy, okay.

So, uniform temperature, no net flow of charge or energy, if this situation is there, then we say a semiconductor is under equilibrium. Next slide shows a few points about the equilibrium state. Firstly, it is a dynamic and not a static concept. So what it does mean? This means; for example, supposing I take a block; I am talking about static equilibrium; what is static equilibrium? You take as block and you apply forces at the 2 phases.

Let us say these 2 forces are equal. Now the block will not move therefore the block is in a state of equilibrium, but this is static equilibrium because there is no movement, there is no activity. As against this, supposing you had another situation where the same block is bombarded with steel balls from the left end repeatedly and from the right end, okay. So, somebody is throwing steel balls on the block from the left as well as from the right.

And if the block does not move even in this equation because the rate at which you are throwing the balls and the moment that has been imparted to the block from this side is the same as that is impart from this side and the block is not moving, then this is an example of a state of dynamic equilibrium, right. Because there is activity, there is movement, okay but for every process there is an inverse process going on at the same rate.

So this is the point, so equilibrium is the dynamic concept, it is not a static concept. Next point is that equilibrium state is difficult to achieve but a good starting point for modelling of charge transport in semiconductors. So in practice, we may not be able to achieve equilibrium state at all. For example, if I take a semiconductor block and place it in front of you, if you are able to see the block, it means a light is falling on the block.

Now, the block is not under equilibrium, this is the simple situation but the block is at under equilibrium. If it is visible to you, that means light is falling on it, part of a light is being absorbed by the semiconductor but the semiconductor is not emitting light. So, here is an example where the semiconductor is absorbing light but not emitting light. So for every process, there is not an inverse process, right.

For this process of light absorption, there is no inverse process, so it is not equilibrium state for the semiconductor. So, those semiconductors; though equilibrium state is not easy to achieve still it is a very useful starting point because we can show many practical situations to the deviations from equilibrium, so equilibrium is like a land mark. If you know the landmark then with reference to the landmark, you can understand the locations of many other things.

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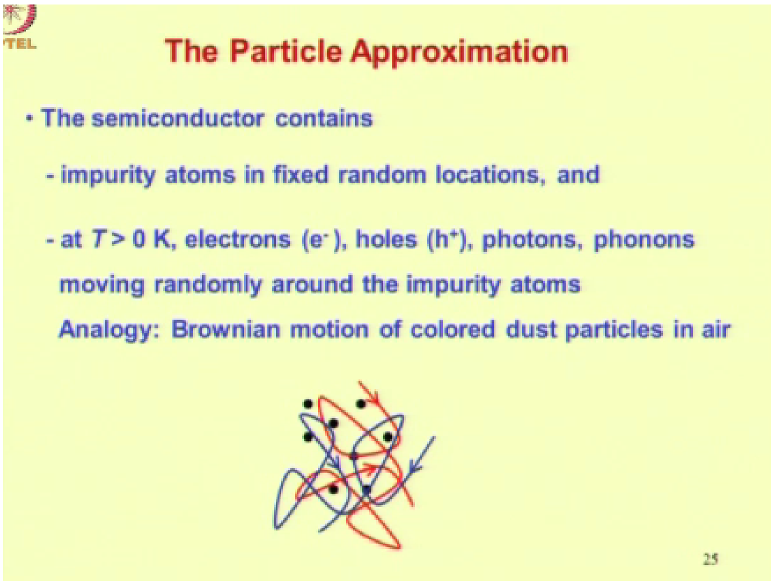

So, in a lighter vein; I say that the peace of mind is like equilibrium of the mind, right. Now, we know that peace of mind is very difficult to get, equilibrium is similarly difficult to achieve. Now, let us begin our model for the equilibrium, the slide shows the important approximation that we make namely the particle approximation. So, in this approximation we visualise the semiconductor will containing the impurity atoms in fixed random locations.

And for temperature greater than 0K, electrons hold photons and phonons moving randomly around the impurity atoms. So, the electrons, holes, phonons, photons, impurity atoms all these are regard as particles. Impurity atoms are fixed, whereas the other particles are moving above. So, the analogy for this is also shown here in the diagram, it is Brownian motion of coloured dust particles in air.

So, I shown on the slide here the black dots are fixed impurities but located randomly and then the arrows around it show the path of the other particles namely electrons, holes, photons and phonons. Now, only 2 colours are shown here to avoid fluttering of the figure. So, you could regard for example red to the indicating holes and blue to be indicating electrons.

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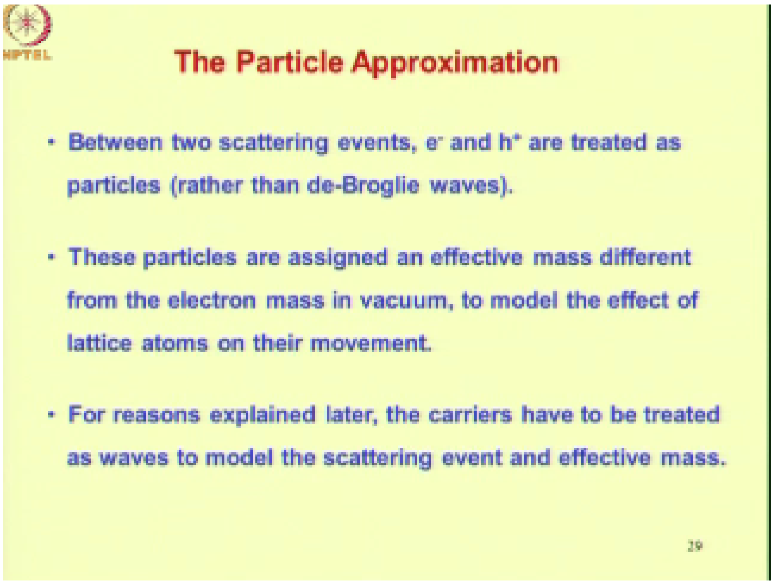

And now similarly you can add 2 more colours and then you can visualise the picture in which phonons and photons are also present. So, it is all particles, interaction between particles, that is what we are visualising in this model, the particle approximation. Let us explain this particle approximation, the slide shows the electromagnetic and elastic waves generated from vibrating lattice atoms are treated in terms of their particle equivalence, photons and phonons respectively.

So, photons and phonons are actually representing waves, photons represent electro magnetics waves and phonons represents the waves in the lattice atoms because of vibrating lattice atoms. Now, this point has been explained in detail in the first level course on solid state devices, you can refer to my lectures there. The early lectures on equilibrium state explain in detail how the various waves are formed. Let me summarise the result for you here.

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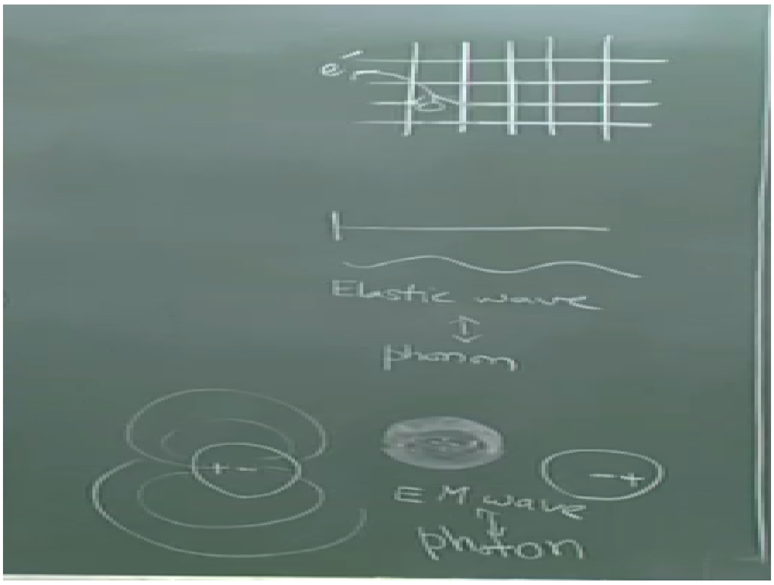

Suppose, the semiconductor such as silicon is shown by equidimensional representation like this were at each point of intersection you have a silicon atom and the 4 bonds from the silicon atoms to the neighbouring silicon atoms are indicated by this 4 lines. So, this is the picture for silicon at 0K. Now, when you increase the temperature beyond 0K, what happens is, that in a sense you have set each of this points in vibration.

Now, imagine a situation where this atom, let us say starts vibrating. Now since this atom is connected to other atoms, it will set other atoms in vibration also just like a rope. For example, if you visualise this line of silicons atom connected together as a rope and now if I flex this end of the rope, you know that it will send out a wave. Now, this wave is called an elastic wave.

The waves in rope or waves in water repels in water, when you drop a stone, these are all examples of elastic waves. So, this elastic wave of silicon consisting of silicon atom, its particle equivalent is referred to as a phonon because some waves in solids are elastic waves, the particles of elastic waves are like particles of sound that si why the word phono; right, that is how the word phonon had arisen.

Now, vibrating silicon atom can also give rise to electromagnetic waves how? Let us magnify this point and show the details of the atom consisting of the nucleus; positively charge nucleus and the electron cloud around it. So, the picture is like this, a positively charge nucleus and you have the cloud of electrons around it. Now, when the atom is in vibration, the centre of the electron cloud and this centre of the nucleus that is indicated by positive charge will not be the same as a function of time.

For example, the picture could be as follows. At some instant of time, the centre of the electron cloud it shown here by negative sign can be displaced from the centre of the nucleus as follows. So, the electron cloud has moved toward right as compared to the nucleus and at another extreme you can have a situation where the positively charge nucleus is to the right of the centre of the electron cloud.

So, the centre of the electron cloud is negative and your nucleus is on the right hand side. So this is an oscillating atom, right. At one end of the oscillation, you have the positively charged nucleus towards the left of the centre of the electron cloud, at the centre of the oscillation you have both of them coinciding here; electron cloud and the nucleus are concentric. Both centres coincide.

Now, here the nucleus has move to the right of the electron cloud, centre of the electron cloud. So, you see that an vibrating atom of a semiconductor is like an oscillating dipole, it is nothing but an oscillating dipole. So, dipole is an arrangement, where you have a positive negative charge with a nonzero separation. Now, if this dipole the distance between the positive and negative charge goes on changing, right that is what is happening, it is called an oscillating dipole.

Now, you know from the course on electromagnetic field that oscillating dipole is a source of electromagnetic wave. So, you will have the waves emanating from this oscillating dipole; emanating from oscillating dipole. Now, the particle equivalent of electromagnetic wave is a photon. So, like elastic wave can be treated in terms of phonons, particle equivalence; you can have electromagnetic wave from a vibrating silicon atom and its particle equivalent will be called photon.

So, that is how we visualise the semiconductor at t greater than 0K as photons and phonons moving about randomly and in addition you have electrons and holes. So, you can have a situation where a bond may break creating a free electron so this is a free electron and leaving behind a hole, so a large number of such bonds may break and therefore you have electrons and phonons.

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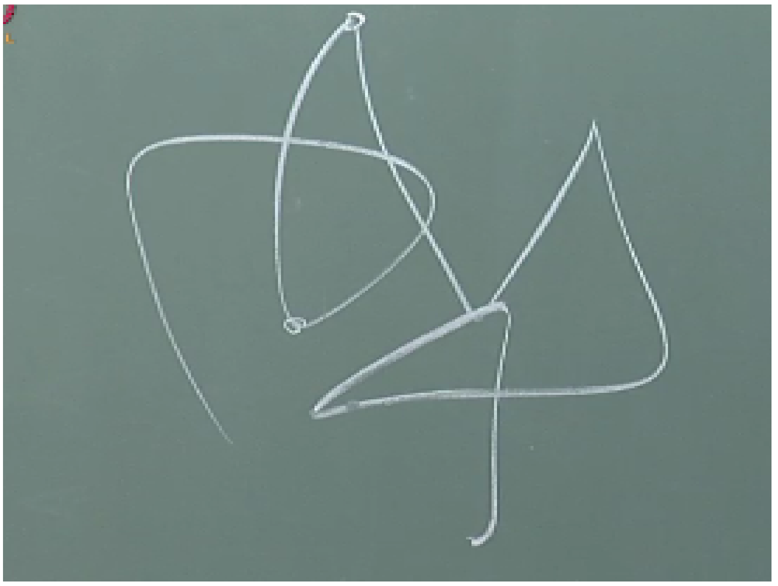

So, this is the picture. Now, let us look at the slide again; between 2 scattering events electron and holes are treated as particles rather than de Broglie wave. Now, the particle approximation that we are making is valid between 2 scattering events, so you know from your first level course that the electrons and holes move around randomly like this and they undergo scattering from impurity atoms phonons or other carriers.

So, between 2 scattering events, you are treating electrons and holes as particles. The scattering event itself cannot be treated classically, okay or electron cannot be treated as a particle to model the scattering event correctly. Similarly, we will have to assume that between the scattering events though the electron or holes is a particle but its mass is not the same as the mass of the electron in the vacuum.

So, electrons and holes have an effective mass. Now, this point is shown in the slide, the particles are assigned and effective mass different from electron mass in vacuum to model the effect of lattice atoms on their movement. So, this movement of electrons or holes is happening in a lattice unlike electrons and holes in vacuum. So, therefore lattice atom will influence this movement and that is the influence that you are capturing in effective mass.

Now, as we will be explained later, the carriers have been treated as waves to model the scattering event and effective mass. So, we are pointing out the limitation of the particle approximation that between the 2 scattering events the electron or hole is a particle but the scattering event itself and the fact that the electron or hole between scattering events has a mass that is different from the mass in vacuum.

So, the scattering event and this effective mass have been treated quantum mechanically that is assuming the electron to be a wave. So, as just for clarification quantum mechanical treatment means that the treatment starts from the Schrodinger equation, a classical treatment means the treatment start from newtons laws, okay. So, particle approximation means you are treating the electron in terms of newtons laws or newtons equations.

"Professor - student conversation starts" At this point, a student seems to have a doubt, yes what is your doubt? Sir, so you said that (()) (46:47) to be visualised as electrons, holes, photons and phonons, so where do you consider the lattice atoms? Okay. So, the question is what happens to the solid lattice atoms? "Professor - student conversation ends" When we say that semiconductor consists of electrons, holes, phonons and photons, where are the lattice atoms gone?

Now, what we have done is that we have observed the effect of lattice atoms in 2 ways. 1 is; when we say that there are phonons; streams of phonons moving about it, they actually represent the vibrating lattice atoms. So, it is like once you have brought about the phonons moving about randomly then you have capture the effect of lattice atoms. So, now you can forget about the lattice atom instead you think in terms of phonons, which are moving above.

Another thing that we have done is; we have assigned the electrons or holes in effective mass different from the mass in vacuum. So, in the process we have taken into account the effect of the potentials of the lattice atoms on the electrons and holes. So, the picture is fairly complete in terms of electrons, holes, phonons and photons and the impurity atoms. We are toward the end of this lecture, so let us make a summary of the important points.

In this lecture, we first pointed out the phenomena of carrier transport particularly semi classical carrier transport that we want to explain, this phenomena, where drift diffusion, thermo electric current then velocity saturation and negative resistance, then velocity overshoot effects and Ballistic transport. Then, we began qualitative modelling of this phenomenon.

We discussed the particle approximation in detail in which we pointed out that we will treat electrons, holes, electromagnetic waves and lattice vibrations or lattice waves as particles, however around fixed impurity atoms but located randomly.