Solid State Devices
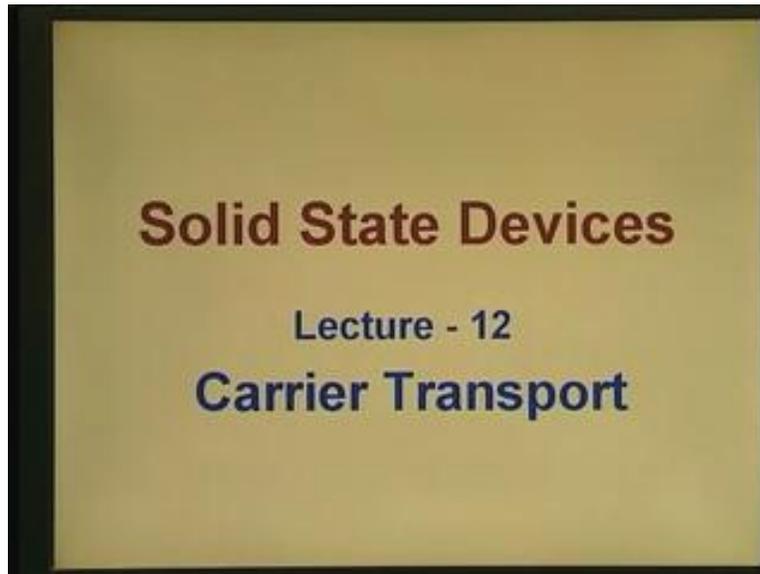**Dr. S. Karmalkar**
Department of Electronics and Communication Engineering
Indian Institute of Technology, Madras
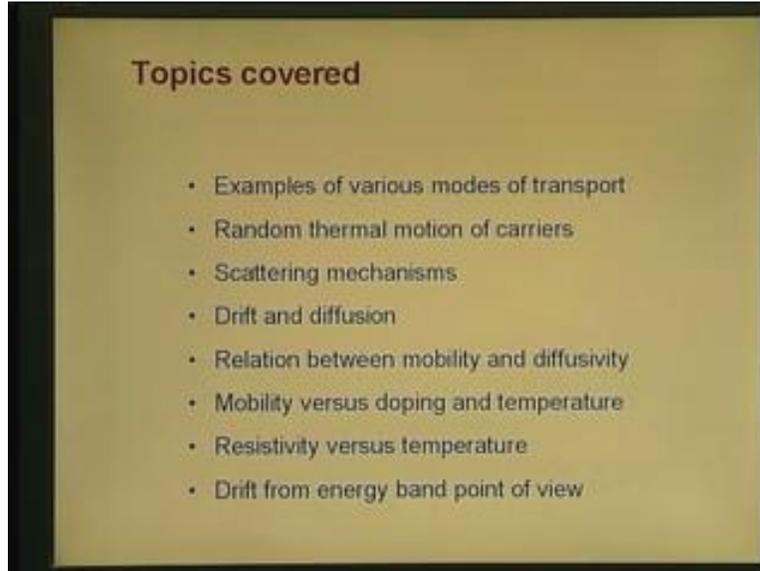**Lecture - 12**
Carrier Transport

So in the 12th lecture of this course we are beginning a new topic that is Carrier Transport.

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So far we have seen how the Carrier Concentration is decided in a semiconductor. Now in this lecture we would like to see how the carriers can be transported and what are the various ways in which the carriers can move?

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Some of the topics which will be covered in this lecture are: Examples of various modes of transport, the random thermal motion of carriers, scattering mechanisms, drift and diffusion, relation between mobility and diffusivity, mobility versus doping and temperature, resistivity versus temperature and drift from the energy band point of view. So let us begin with the examples of various modes of transport.

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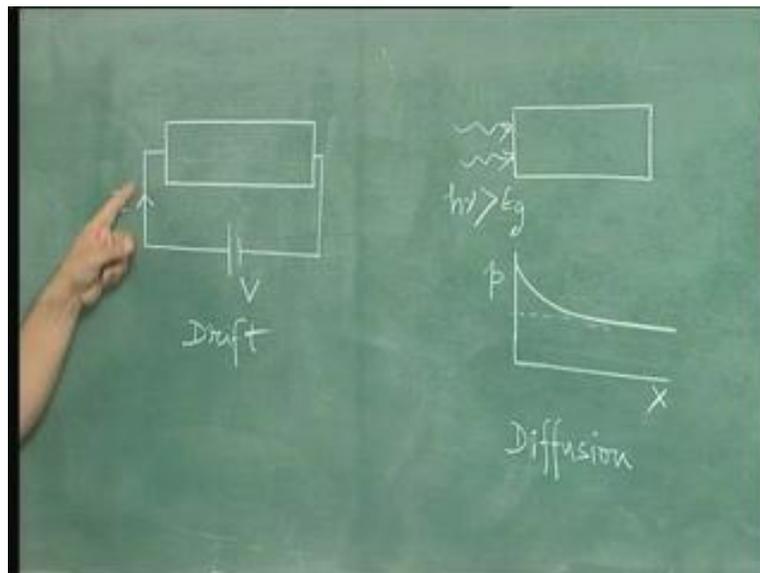
Now, this is an example of the drift transport. Here to a semiconductor sample a voltage has been applied which results in a current. The flow of current in the semiconductor here in this case is due to drift. Here is another example of transport where the sample is being

illuminated at one end. The assumption about the light that is falling on a sample is that the quantum of energy or the energy of the quantum of photon here is greater than the energy gap so that the photon can help in creation of electron hole pair by breaking of silicon bond.

Since the light is going to be absorbed within a short distance from the surface about a micron or so the excess carriers or extra carriers will be created only near the surface. Therefore the concentration of carriers near the surface will be higher than in the bulk and concentration gradient of carriers is therefore established; this is shown here with the help of a graph. The whole concentration is more at the surface and it is decreasing to the equilibrium value in the bulk.

Similarly you can have variation for the electron concentration because electrons and holes are generated in pairs. Now because of this gradient of the concentration for the holes you will have a tendency for the holes to move from left to right and there will be a whole current due to diffusion. Similarly you can also have an electron current due to diffusion in this case because electrons are more here than the inside.

Let us look at another example of Carrier Transport. Here you can see that there is a sample to which two contacts have been made and one contact has been kept at a higher temperature than the other contact. This can be easily achieved, for example by placing a soldering iron near this contact so this contact becomes hotter than this contact. In fact the tip of the soldering iron can be used as a contact here. And if you connect an ammeter between the two you will find that there is a current flow through the ammeter and the ammeter will show a deflection. If the sample is a p-type then you will find that the current is moving from cold to hot junction.

In the n-type sample the polarity of the current will be the opposite i.e. the direction of flow of the current will be opposite. So here there is a current because of temperature gradient. The temperature here is different from the temperature here and therefore there is a current established so this kind of current is called thermo electric current. Finally this is another example of Carrier Transport.

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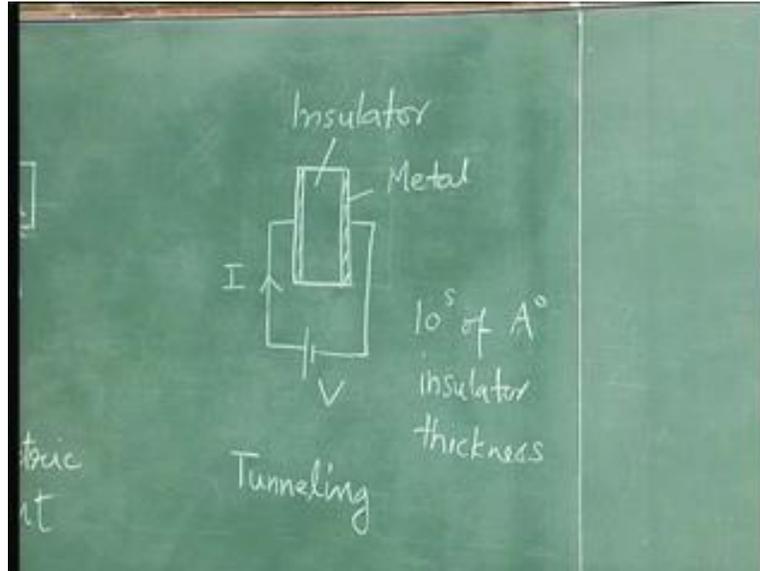
Here this is an insulator and you have two metal contacts on either end so this is just like a parallelepiped capacitor. We are assuming that this is a perfect insulator. So strictly speaking when you apply a voltage between these two metal contacts there should be no current. However, if the insulator is very thin, meaning of the order of few tens of Angstroms $(10^s \text{ of } \mathring{A})$ insulator thickness then you will find a current in response to a voltage. This current flowing through the insulator is because of tunneling.

Now these three mechanisms of transport namely: Drift, Diffusion and Thermoelectric Current are referred to as Semi Classical Mechanisms. Although the basic picture is quantum mechanical in nature of this transport we can use some simplifications after which the transport can be treated using the classical principals of Physics without the need to invoke quantum mechanics.

On the other hand, this particular mechanism that is tunneling is a quantum mechanical phenomenon. That is because you cannot explain it without the help of quantum mechanics. No simplification is possible so that you can use classical mechanics or classical physics to explain this particular phenomenon. In this course we will be concentrating on Drift and Diffusion which are mechanisms of semi classical transport. Now let us see the things we are going to discuss about these mechanisms.

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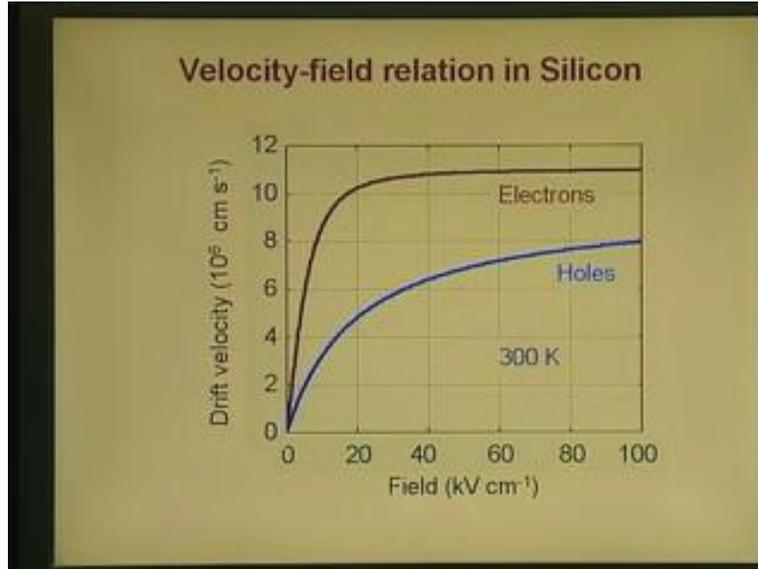
First, this is a slide showing the Drift Transport as to how the drift velocity changes if you vary the field in the semiconductor. That is, how the velocity of the electrons and holes resulting from drift end changes. It is important to note the magnitudes of the quantities involved, so you see that beyond about 20 kilovolt per cm, the velocity of electrons is almost saturating even though you increase electric field there is no change in the velocity and this saturation velocity is about 10 to the power 7 cm by s. For the holes the saturation occurs much later which may be around 100 kilovolts by cm.

This is the picture in silicon at 300k. For small electric fields however, the velocity of electrons and holes increases linearly with electric field. So here for small electric field means for electrons which are below 10 kilovolts by cm. You have a kind of a linear segment of this particular curve. These are two things we have to explain, i.e. for small electric fields the drift velocity is linearly related to the field whereas for high electric fields the velocity saturates. So how does this happen? Now, it is necessary to note that 10 kv by cm is equal to 1v by mu m.
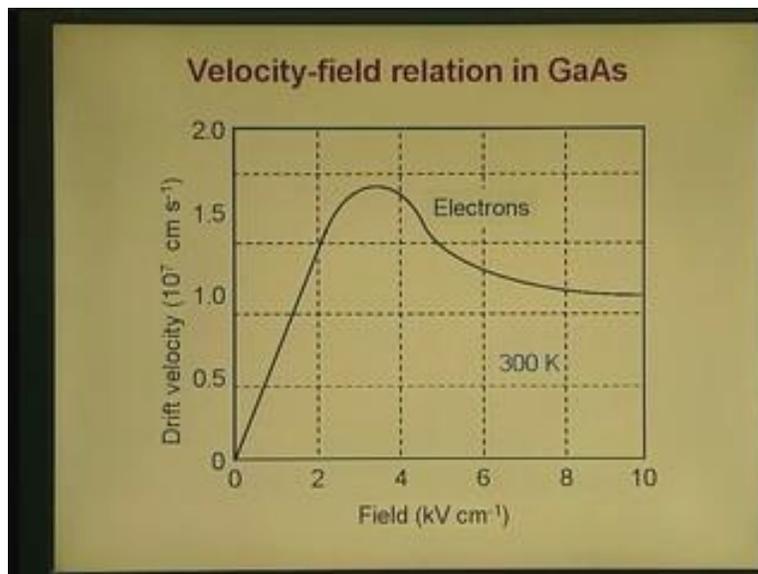
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So this gives you a feel for the quantity 10 kv by cm of electric field means 10 cube v by 10 to the power 4 mu m which is 1v by mu m. So those are the kind of fields that are involved in this.

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Next, let us look at velocity field relation in a compound semiconductor such as Gallium Arsenide. Here the behavior is shown for electrons. You find here that for high electric fields there is a saturation and for low electric fields there is a linear behavior but in between these two linear and saturation regions there is a region where the velocity peaks and then falls off. Therefore there is a region here where the velocity decreases with the

electric field. This is a unique feature of the drift transport in compound semiconductors in general.

The order of magnitude of the quantity is involved here, and the saturation velocity is of the order of 10 to the power 7 cm by cm by s which is of the same order as in silicon for electrons. However, you can see here that the fields at which the saturation occurs is somewhat lower than the field that we encountered in silicon. So here, by 10kv by cm saturation is taking place. And what is more important here is that the linear range is occurring at much lower electric fields.

It is restricted to much lower electric fields and therefore the slope of this particular linear portion which is the mobility, that is the ratio of the drift velocity to field in the linear region, this is called the mobility, so this ratio or this slope or the mobility is much higher in the case of gallium arsenide than in the case of silicon. Whereas a linear range was about 10kv by cm in the case of silicon, here it is about 2 kilovolts per cm. So you see a difference of five times between the mobility of silicon and gallium arsenide of electrons. The mobility of electrons in gallium arsenide is five times of that in silicon.

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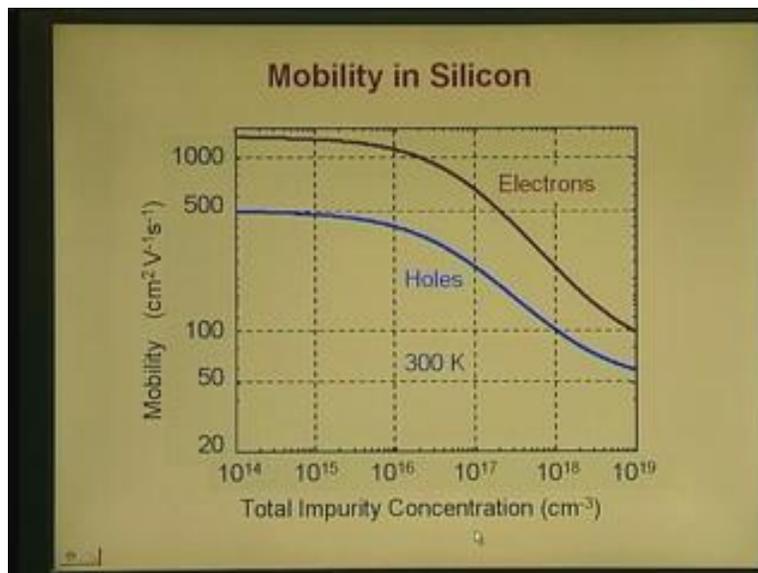
Now let us discuss the behavior of the mobility i.e. the ratio of the velocity to the electric field in the linear region. This particular parameter varies with the total impurity concentration within the semiconductor. This is something that we will like to explain. It decreases as your total impurity concentration increases. Also note that the mobility of electrons is higher than the mobility of holes. Another point to note is that, what is being plotted here is total impurity concentration. The concentration of electrons for example in an n-type semiconductor would depend on the difference between the n-type doping and the p-type doping or it is dependent on the net doping. So carrier concentrations depend on the net doping whereas the mobility depends on the total doping i.e. the sum of the doping concentrations, this is what is important to see here.

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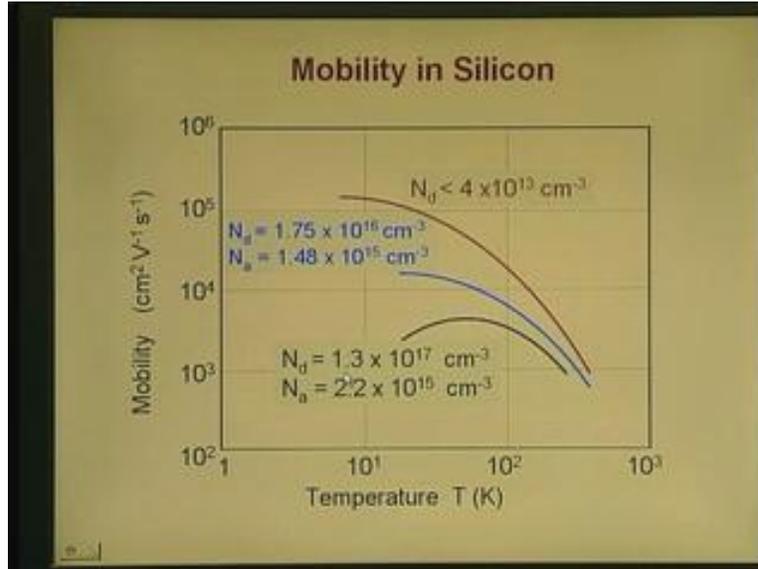
Next is variation of mobility of silicon with temperature for different doping levels. You can see from here that the mobility increases for low temperatures as the temperature is increased. It reaches a peak and then it falls off as a temperature increases so this is the behavior that we would like to explain. For higher and higher doping the mobility is lower, that is, the peak goes on decreasing. So this is the peak for 4 into 10 to the power 13 cm cube doping, this is the peak for a sample in which you have both n-type and p-type doping. So this peak will depend on the sum of these two quantities. And this peak here is for even higher doping levels as shown here. So this is another thing we would like to explain.

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Then we come to the diffusivity or the constant associated with the diffusion mode of transport in analogy to the mobility which is the constant associated with drift transport. It turns out that the diffusivity can be calculated from the mobility using this relation: diffusivity is equal to mobility into thermal voltage at any temperature D is equal to mu V_t, This relation is called the Einstein relation. We will show how this relation is derived.

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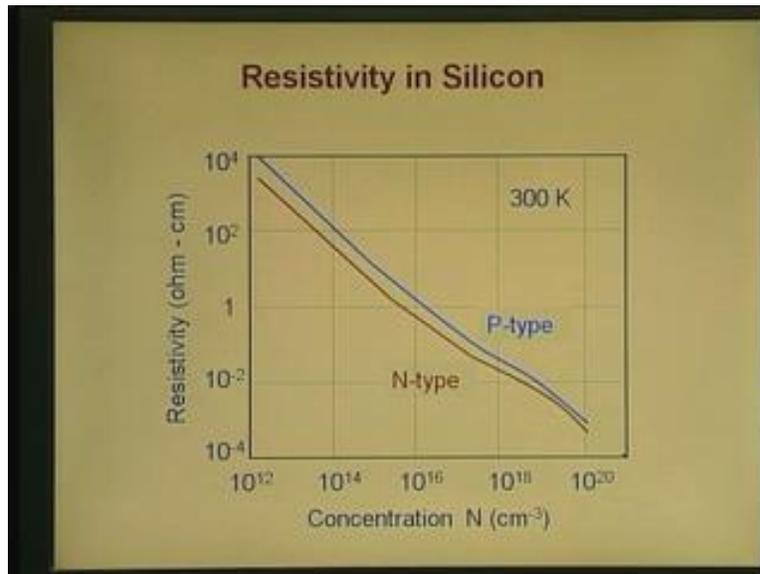
Finally we will see the resistivity of the semiconductors. Here we have shown resistivity varying with doping concentration. The concentration here is doping concentration for p-type and n-type. This behavior is what will see by combining the mobility and the effect of doping or carrier concentration behavior.

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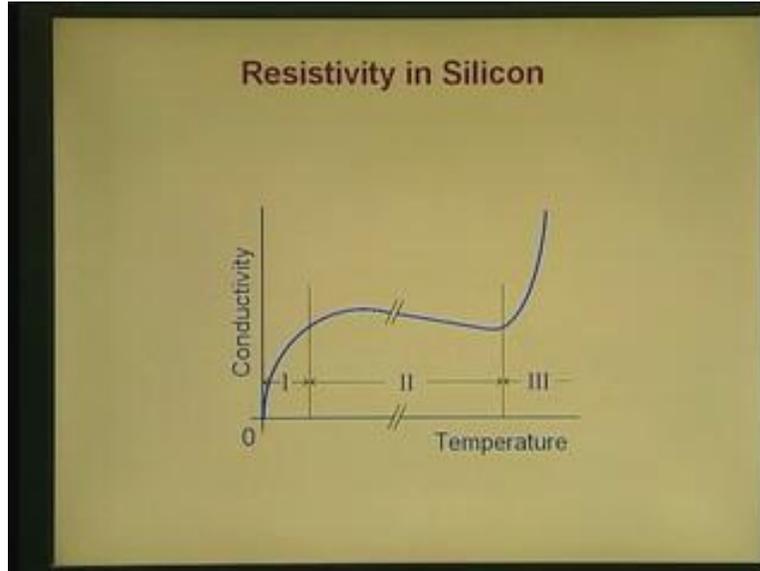
Another important aspect of the resistivity is the variation of the resistivity with temperature. Here, the reciprocal of resistivity that is conductivity has been plotted with temperature. You have the three regions here corresponding to the extrinsic range which is two. This is the range in which the dopends are ionized partially and this is the intrinsic range. You see that, in the extrinsic range the conductivity increases and then decreases, this is something that we will show, the conductivity or the resistivity. Now let us begin with the explanation for these mechanisms of transport. As we will see these mechanisms of transport are dependent on the random thermal motion of carriers at any temperature. So the first topic that we will discuss is the Random Thermal Motion of Carriers.

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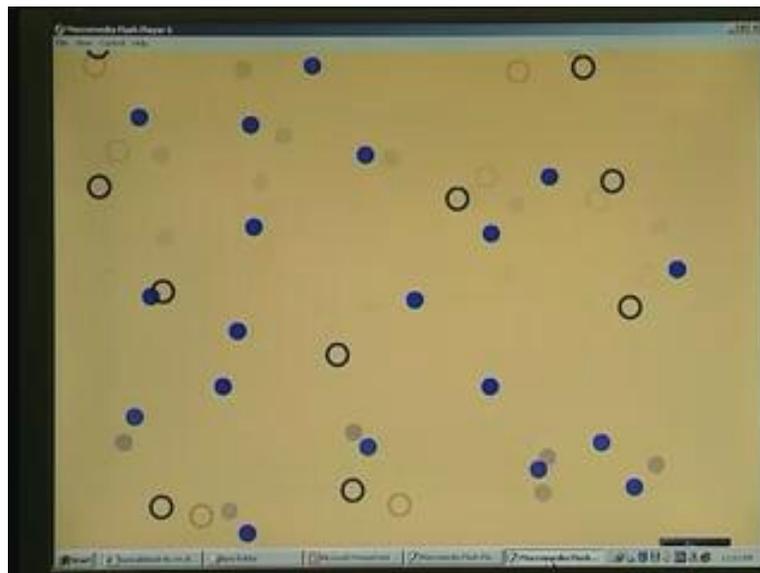
Now we will start with the picture under equilibrium. This is a slide we showed which is under equilibrium condition. This slide shows generation and recombination of carriers. So, under equilibrium generation is exactly balanced by recombination. A carrier is generated and it stays alive for sometime and then it recombines. Now between the point or the instant the carrier is generated and the instant the carrier recombines it moves around. Now, if you also include this movement then the picture will be something like this. This is the random motion of carriers, this motion can be the path of a carrier between generation and recombination, it is something like this where the carrier is generated, so point one is generation and point two is recombination.

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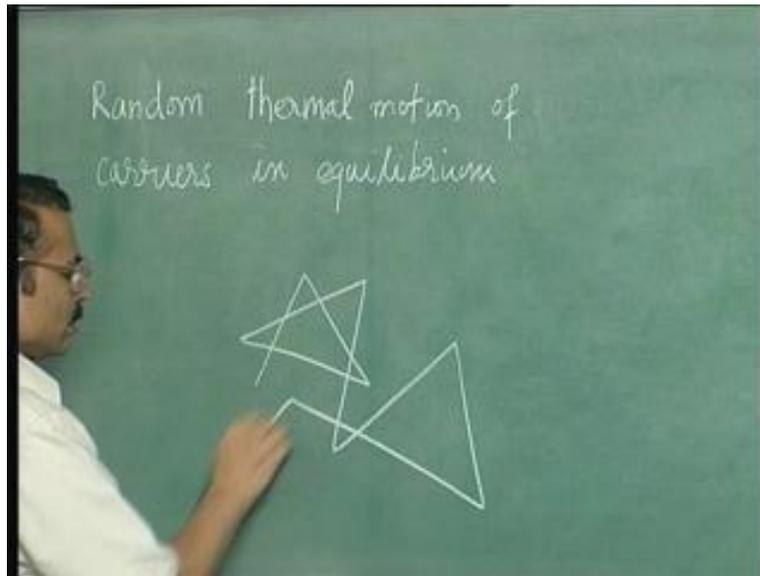
So between generation and recombination the carrier is moving about in the crystal. Now notice the path of the carrier because the temperature is greater than 0 and the carrier has a thermal velocity and that is why after it is created or generated it starts moving. But then when it moves it also finds the other particles which are present and as a result it is getting scattered by the other particles. It collides with other particles and its direction of motion is changed. So each of these points here where you see a change in the direction of motion is a point that shows scattering.

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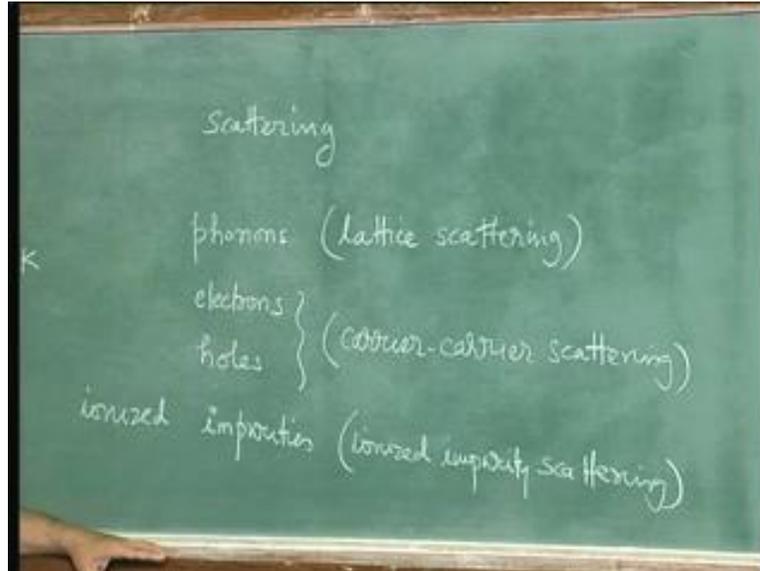
So this is the result of collision of the particle with other particles which are present. What are the other particles which are present? In the previous discussion we have listed these particles as phonons or vibrating silicon atoms, then electrons and then holes. And now, if you have a doped semiconductor you must also include the impurities. In particular, we must note that the impurities are ionized at any temperature greater than 0, although not fully but at least partially. In the extrinsic range the ionization is complete, so we can say ionized impurities. Although some scattering does take place from neutral impurities let us not bother about it.

Now notice that we have not listed photons here because the photons have a small momentum and therefore the effect of this collision on the carrier with the photon is not significant so we will not bother about it. So we are left with these particles; phonons, electrons and holes and ionized impurities.

For example, an electron which is moving can collide with phonon, can collide with electrons or holes or can collide with ionized impurities. This form of scattering of electrons with phonons is called Lattice scattering or Phonons scattering. It is called Lattice scattering because phonons are nothing but vibrating silicon atoms at lattice sides so that is why it is called Lattice scattering. The scattering with electrons and holes is called carrier-carrier scattering and the scattering with ionized impurities is called ionized impurity scattering.

Now, here it is important to note how the scattering of an electron in carrier-carrier scattering and ionized impurity scattering is different from that in lattice scattering. You see, scattering with a phonon is a physical collision between the carrier and the atomic site whereas in the case of the other two mechanisms of transport here; this particular scattering is because of action at a distance and it need not involve a physical collision because this is collision between charged particles.
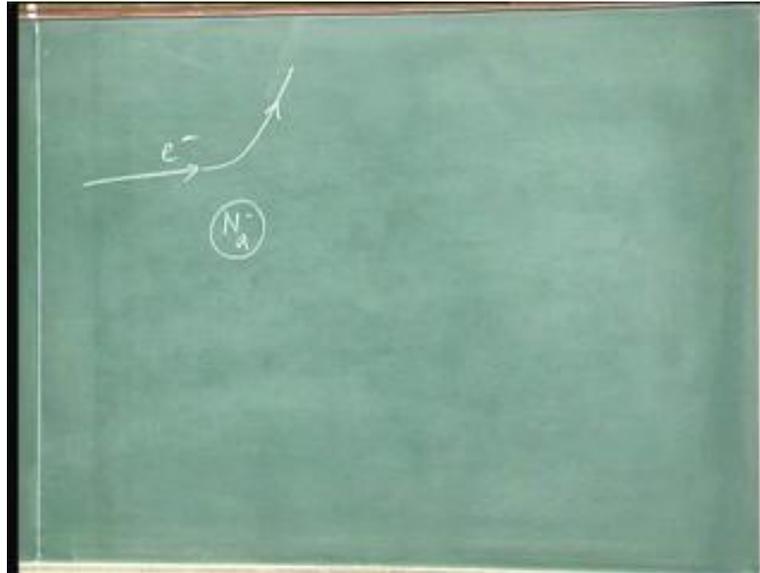
For example, supposing an electron is moving like this and it sees an ionized acceptor impurity then it is going to be repelled as it comes near to impurity and therefore its direction will change as something like this. So this is scattering that is taking place, it is action at a distance, not necessarily a physical collision. Similar comments apply to electron colliding with another electron or electron colliding with hole. It is important to note that an electron colliding with the hole, when the collision is action at a distance it results in scattering whereas if an electron meets a hole physically then a recombination can take place.

It is very clear that the chances of recombination are less than chances of scattering between the electron and hole because for recombination you require that they physically meet each other. So one must not think that whenever there is a collision the electron and hole is always resulting in a recombination, not necessary, it can be resulting in scattering. These are the mechanisms by which the carrier is getting scattered and that is why it results in a path something like this, and that is why you have a random motion of carriers.

Now, please understand the difference between scattering and reflection. In reflection the direction of motion of the particle which is getting reflected can be predicted. But in scattering the direction of motion of the particle which has encountered a collision cannot be predicted exactly and that is why there is some randomness involved, that is the difference between scattering and reflection.

Coming back to this picture of the random thermal motion; the distance between any two successive collisions that a carrier travels which is this distance or the distance here is called the mean free path, the free path. And if you average the free paths for all these different periods of travel you get what is called the mean free path.
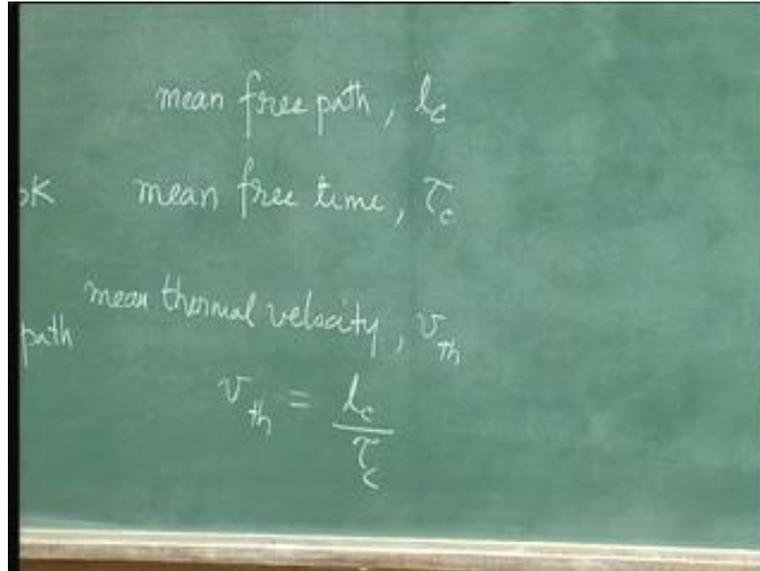
Normally we use the symbol l_c to indicate the mean free path, c stands for collision, so mean free path between two collisions. It is the average of all the free paths that the carrier undergoes between collisions because the paths between collisions will not be the same they are all distributed because it is a random picture, so the average of that is the mean free path.

Now the time between any two collisions, that is the time of the free path is called free time and like mean free path if you average the free times you get mean free time that has a symbol tau_c. So tau_c or mean free time is another parameter. Finally you have the parameter namely the thermal velocity which is also a mean. This is route mean square average (RMS) which we will see later, and this is the thermal velocity. So one can roughly use the relation V_{th} is equal to l_c by tau_c so average thermal velocity is the mean free path by mean free time.

Now let us look at some of the properties of this random thermal motion. Specifically we will see that this picture implies intense motion but no net motion. What is the meaning of this?
The meaning of this is that the velocity of the carrier which is undergoing this motion is very high, it is of the order of 10 to the power 7 cm by s at room temperature so there is intense activity. But on the average the motion does not amount to anything so it is no net motion i.e., there is no motion in any single direction. The effect of various small motions during the mean free path is getting cancelled. Let us look at this aspect in greater detail.

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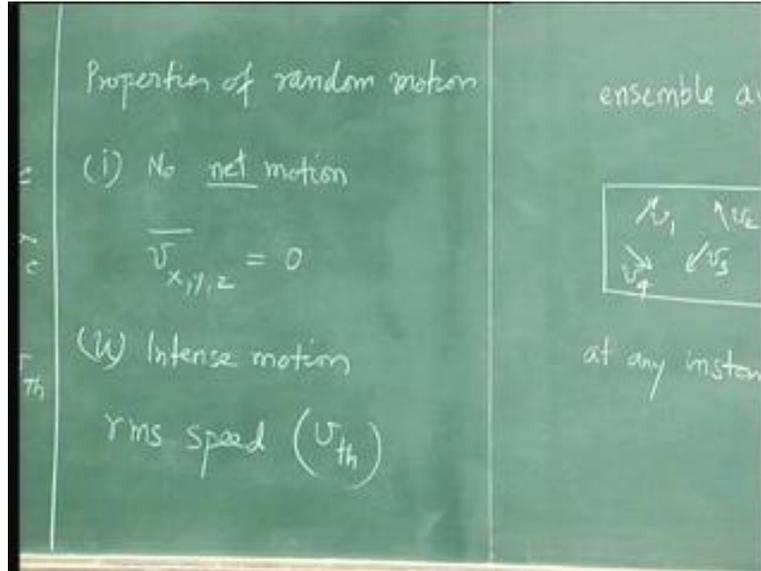
Properties of random motion: First is no net motion, the word net is important. So what does it mean? There are several ways of interpreting this particular statement. One way of interpreting this is in terms of average of the velocity. The average velocity of the carrier x, y or z components is 0. Now the question is, how do you determine this average? There are two ways to determining the average. One is called the ensemble average.

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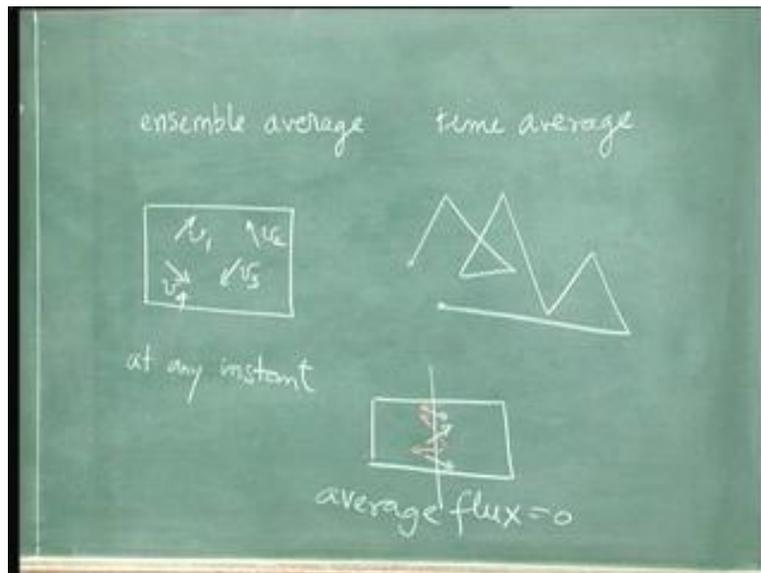
This means, supposing I look at the picture of the semiconductor and sufficiently I take a large population of carriers at any instant of time and then if I freeze the picture and note the velocities for the population, and then if I sum up all these velocities and divide by

the number I will get this average as 0. In other words sum of the velocities will be 0. So this is one interpretation of no net motion. Another interpretation of no net motion is the time average.

Here you follow the path of a particle over a sufficiently long period of time, so you are looking at a single particle over a sufficiently long period of time. Here in the ensemble average you are looking at a sufficiently large number of particles at any instant of time. Here in the time average you look at a sufficiently long duration of time but you monitor a single particle and then you will have this path that we have shown.

Now, what the time average gives you is, if you average this particular velocity over a long period of time, here the velocities are in this direction, here it is in this direction and here it is in this direction and so on. So you find out the time average which amounts to taking the net displacement of this particular carrier over a long period of time then that displacement would be 0, that is, the net displacement is 0. So, for time average of the velocity you average all these velocities for a single particle during different instants and then you will get that average as 0. So that is another interpretation of the no net motion. So a carrier is not really getting displaced, even though it is moving about it ultimately returns to the point.

Another way of interpreting no net motion is, if you take a plane and see the average flux across this plane, which means you observe a certain duration of time and find out how many carriers are crossing from right to left and you also observe how many cross left to right, then you will find the number of carriers crossing from left to right is the same as number of carriers crossing from right to left in that duration. The average flux is 0 in any time duration across any plane. This is another interpretation of no net motion.

Now what is the meaning of intense motion? If I were to take the speeds of the particles that I have noted here, I ignored the direction; instead of the velocity I take the speed, but I ignore the direction and take only the magnitude of the velocity and then I take all these speeds and then I find out the root mean square average, that is, you square the speeds then you take their mean and then you take the square root, so this root mean square velocity RMS speed is very high and that is called v thermal.

The meaning of intense motion is, though the average of the velocity is 0 the root mean square speed is very high. We must also remember some figures. What is the meaning of this intense motion? Thermal velocity as we said is of the order 10 to the power 7 cm by s. The mean free time between collisions is of the order 10 to the power minus 5 cms and the mean free time between collisions as you can see, if this is 10 to the power 7 and this is 10 to the power minus 5 this is of the order of 10 to the power minus 12 seconds or picoseconds. So l_c which is 10 to the power minus 5 centimeters means it is 0.1 1 microns; tau_c is about 10 to the power minus 12 seconds that is 1 picosecond and thermal velocity is 10 to the power 7 cms by s. So tau_c (10 to the power minus 12s) means that within one second we have 10 to the power 12 collisions, it is really a large number of collisions. These are the parameters we must remember for 300k or these are the values given for 300k. Generally these values hold for different semiconductors, although from

semiconductor to semiconductor these parameters will definitely change somewhat. Now we will have to see, on the basis of this random thermal motion how can we explain the various mechanisms of transport?

One can start from any one of these pictures under equilibrium for this purpose. It turns out that it is very easy to explain the various mechanisms of transport using this particular picture as a starting point.

The transport results are; whenever you disturb the equilibrium by external excitation, the excitation may cause a potential gradient or a concentration gradient or it could cause a temperature gradient. That is how you get drift, diffusion and thermo electric current. So we want to explain if this is the picture under equilibrium i.e. the average flux is equal to 0 across any plane, then how is it that the average flux will be non zero whenever you apply the excitations that I have just mentioned. Let us draw the same picture on a magnified scale.

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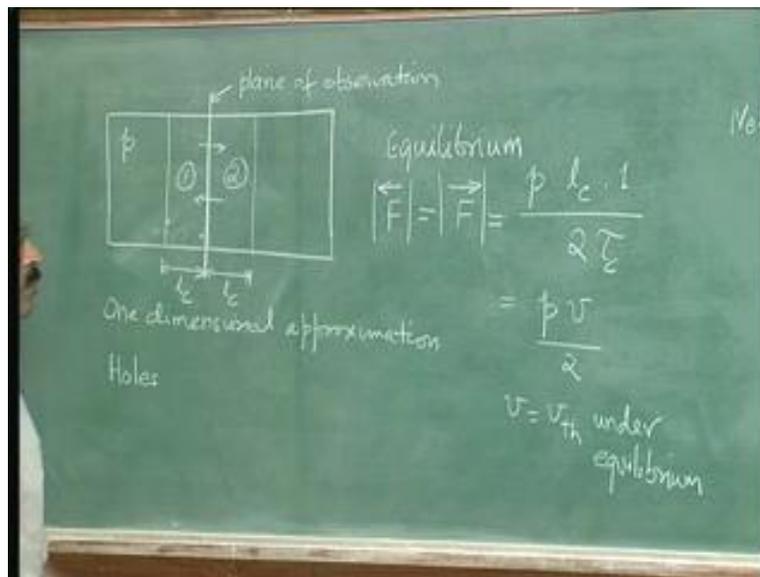
Let us say this is the plane of our observation. And now we want to know, under equilibrium what is the flux of carriers from left to right and what is the flux of carriers from right to left and then when you apply the excitation how these two fluxes are disturbed?

So, if you want to know flux of carriers from left to right let us assume a One dimensional situation and now this particular region that we have shown here is the region in which this distance is equal to the mean free path so this is l_c. It will soon become clear why we are considering a region whose width is equal to l_c. To find out the flux we need to observe the carriers which are crossing this particular plane in any one direction in certain time duration.

Now, if it is a one dimensional situation it is clear that a carrier which is on this side next to this plane of observation is crossing this plane to the right it will cross this plane with the thermal velocity v thermal. Now a carrier which is at a distance l_c here if it is moving to the right then it will just end up crossing the plane by the time it reaches here because it encounters a collision after a distance l_c.

Now all other carriers in between these two points which are moving to the right will always cross the plane. A carrier which is out of this region somewhere here which is moving to the right it will travel a distance l_c and then it will encounter a solution. And after collision you do not know whether it will go this side or that side. We can therefore say that carriers which are within this region and which are moving to the right will cross this plane. Let us talk about holes, we have to talk about holes and electrons separately. So we consider holes and whatever we do for holes can be applied to electrons also. Let us assume that the concentration of holes in the semiconductor is p and it is uniform. So the holes which are in this width and which are moving to the right will cross this plane.

What is the number of these holes? The number of these holes can be written as p the concentration into the volume of that region that is l_c into the area of this particular cross section. Let us assume a unit area of cross section for simplicity so p into l_c into 1 that is p into l_c, so too many carriers are there in this region. Now, exactly half of these carriers will move from left to right and half of these carriers will move in this direction. That is the only way you can have no net motion across any plane. If I want no net motion across this plane for example, if all the carriers in this region are only travelling to the right then none of these are traveling to the left so same thing will be applicable for carriers on these sides and they will only be traveling to the right where I will end up getting a net flux across this particular plane. Since I do not want a flux across any plane that is when there is no flux which is the equilibrium condition then it implies that exactly half of the carrier should move to the right and other half should move to the left and therefore half of this number of carriers denotes the number of carriers moving from left to right. Now what is the duration in which these carriers move?

Clearly the duration is tau_c because we are making an observation during one mean free collision time. It is during this time all these carriers will move from left to right. So in tau_c if you divide this is the number of carriers crossing and tau_c is the time over which this crossing occurs so this is your flux from left to right. Similarly one can show that flux from right to left is also same in magnitude so this is the magnitude of this flux and this is also equal to the flux from left to right and this is under equilibrium.

So under equilibrium this is the flux. We can simplify this relation and we can write this as $\frac{p\ddot{u}}{2}$ tau_c nothing but the random velocity. Under equilibrium this v is v thermal and it is the thermal velocity under equilibrium. Now starting from this particular relation of these fluxes one can show how a net flux can result across any plane.
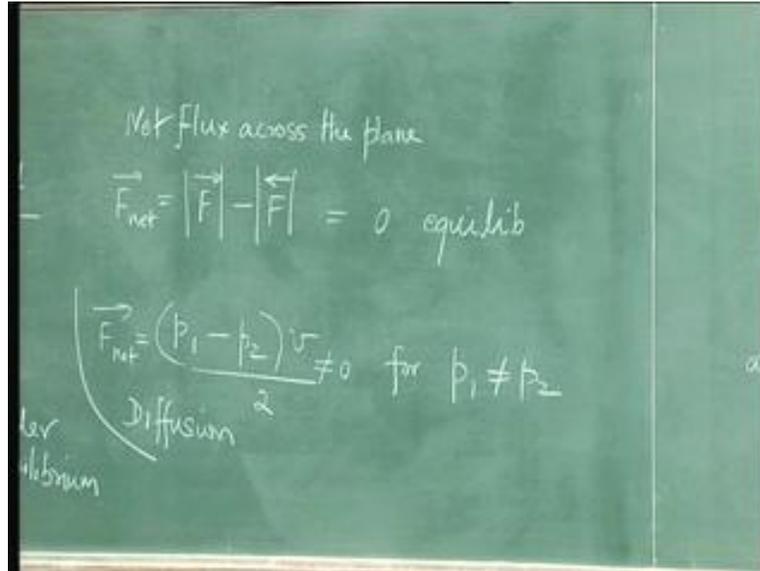
So flux across the plane is F in this direction and minus F in the other direction and these are the magnitudes and that is the net flux across the plane. Now this quantity will be 0 for equilibrium as we have seen. How do you explain that, starting from this point there can be a net flux?

Now clearly if this quantity pv by 2 is different for this region than for this region, now let us call this region 1 and this is region 2 then the net flux will not be 0, what does this mean? This means if p in 1 the concentration of holes in region 1 is different from concentration of holes in region 2 then the net flux will be given by $\frac{(p1-p2)\vec{v}}{2}$ which is the net flux in that direction. So F net is equal to this if it is a non equilibrium situation where p_1 is different from p_2. So evidently this is not equal to 0, if $p_1 \neq p_2$. So this is how a concentration difference in the two regions results in a net flux, this is the diffusion transport. This is the explanation of the diffusion transport, the net flux across any plane because of concentration gradient.

Now we can similarly explain how you can get drift. For example, if there is an electric field in this direction then this electric field will aid the movement of holes from left to right but it will oppose the movement of holes from right to left. So the velocities of all the holes which are crossing in this direction will be reduced. So if you call that velocity as v_2 and you call the velocity of carriers which are moving from region 1 to region 2 as v_1 then you get a difference for the two fluxes.
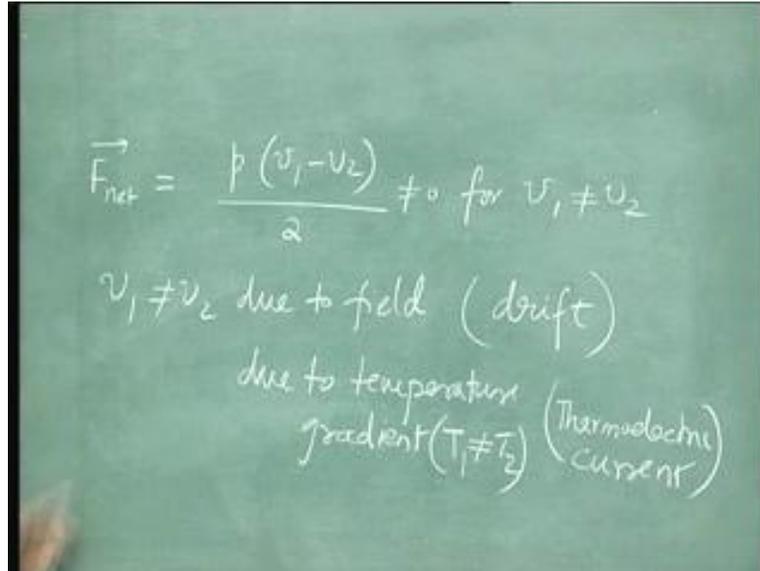
So F_{net} equal to $\frac{p(ΰ1-ΰ2)}{2} \neq 0$ forΰ1 $\neq$ ΰ2. So we just saw that because of electric field v_1 which is this velocity in this direction for carriers is higher than the velocity of carriers in this direction. So if $v_1 \neq v_2$ due to field implies that there is a transport and this is called the Drift Transport. On the other hand v1 can be different from v_2 also because of temperature gradient. If in region 1 the temperature is more than that in region 2 then we know that the random velocity of carriers is a function of temperature, it increases as temperature increases.

So the random velocity in region 1 will be more than the random velocity in region 2. If there is a temperature difference t_1 and t_2, t_1 is more than t_2 you can have $v_1 \neq v_2$ also due to temperature gradient or temperature difference i.e. $(T_1 \neq T_2)$ then this current is thermo electric current. So that is how one can explain both drift and thermo electric currents using this particular equation. We summarize our discussion so far in terms of this important statement.

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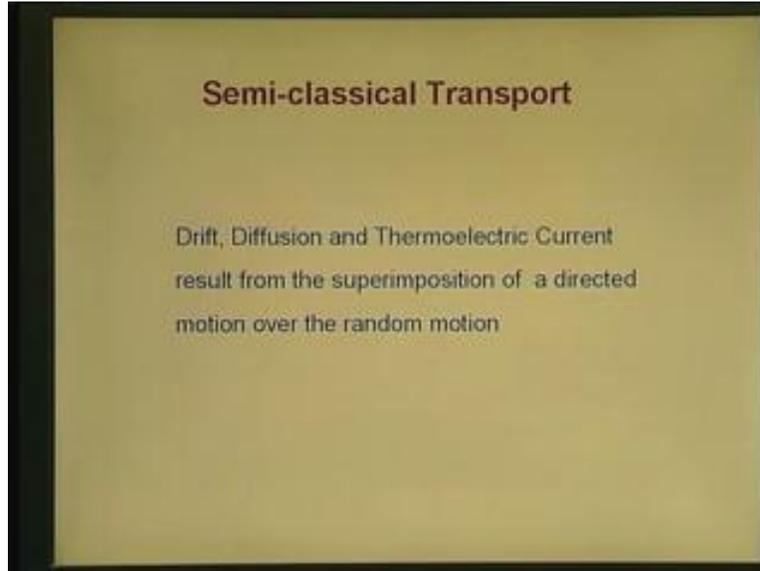
All mechanisms of semi classical transport namely Drift, Diffusion and Thermo Electric Current result from the superimposition of a directed motion over the random motion. So it is the superimposition of a directed motion over the random motion. Random motion is the basis and there is an intense random motion under equilibrium and when you apply the external excitations such as concentration gradient, potential gradient or temperature gradients then a directed motion is superimposed over the random motion. There are interesting analogies to explain this particular concept of motion of carriers in semiconductors, and one such analogy is this.

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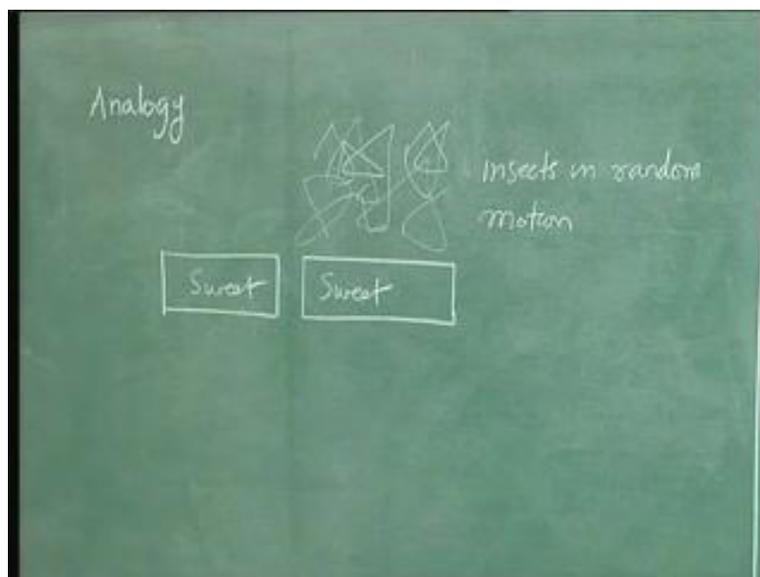
In fact this analogy is the description of a situation that we often see in many of the shops, sweet, meat shops which sell sweets kept in the open. So this is one such box of sweets which is exposed, which is kept open; it is not a good habit but then it turns out that this particular situation is quite useful to explain the mechanisms of semi classical transport. So over this particular open box of sweets you have many flies hovering around undergoing random motion. So you have a population of flies in random motion. Flies or insects we can say in general.

This is the movement of the insects over this particular box of sweet represent the situation of carriers under equilibrium. If you start moving this box of sweet slowly to the left what will happen is these insects will also try to remain above the box of the sweet and therefore they will also gradually move. This is the example of drift transport which shows how a directed motion is being superimposed on the random motion.

Now the word drift indicates a slow movement so what is happening is that when your excitation is small the directed motion is very small compare to the intense random motion and that is why, the carriers are said to slowly drift. Now if you want to give the example for diffusion that is something like this: Supposing you open up another box of sweet here where there are no flies now at this instant. Suddenly what would happen is, some of the flies will try to get over to this side and that is the example of diffusion transport. So they will be randomly moving among themselves and as they are moving some of them will try to move over to this side to remain on this., so that is the example of diffusion transport. This is how one can explain the drift and diffusion phenomena.

Before closing the discussion I would like to emphasis the point that this phenomenon of transport such as by drift, diffusion or thermo electric current has a quantum mechanical basis that we cannot forget. That is why these are not called purely classical phenomena but semi classical phenomena.

What is the quantum mechanical basis we must take into account before applying classical principles to understand this transport? Now you look at the random thermal motion of carriers which is happening because of scattering. This scattering should strictly be regarded as a wave phenomenon for a complete and correct understanding of the transport. Let me explain this with an example; take up ionized impurity scattering.

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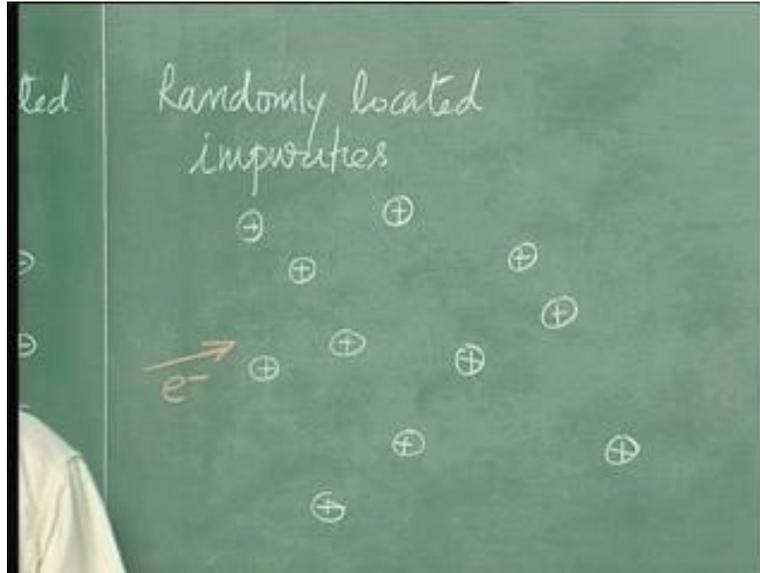
Supposing we have a medium in which you have regularly arranged ionized impurities. In this case let us say these are ionized donors. If an electron is entering this medium and if we use classical principles then it would get scattered as shown by this particular line here. In other words, the direction of motion is going to change because of attractive forces here; then again it is going to be change because of attractive forces here. However, quantum mechanics says that an electron wave entering a periodically varying potential medium cannot be scattered.

In other words, according to the quantum mechanical picture no scattering of this electron wave will take place. Scattering will occur only if the impurity atoms are randomly located as shown here. So quantum mechanics says that if an electron wave enters a randomly varying potential medium, a medium in which the potential is varying randomly then the electron wave will be scattered. It turns out that in a semiconductor the impurity atoms are randomly located so when you apply quantum mechanical principles, you find the conclusion that the electron wave will be scattered.

Once you know the electron wave will be scattered, and how it will be scattered and so on which can be derived from a simple classical picture wherein you assume that this electron is a particle and it is interacting with other impurity atoms. This idea of scattering as a wave phenomenon has been explained with the help of an analogy in this publication.

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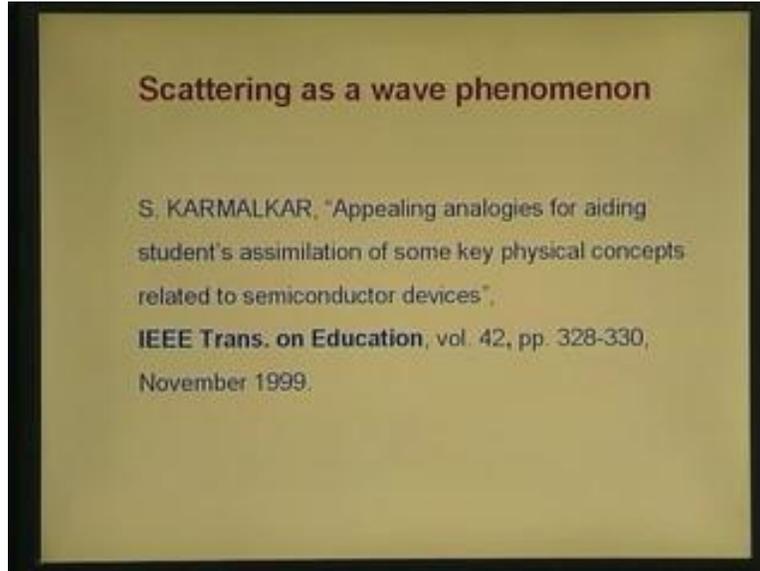
This publication titled appealing analogies for aiding students assimilation of some key physical concepts related to semiconductor devices was published in IEEE transactions on education in volume 42, November 1999 on page number 328. I will briefly describe this analogy here.

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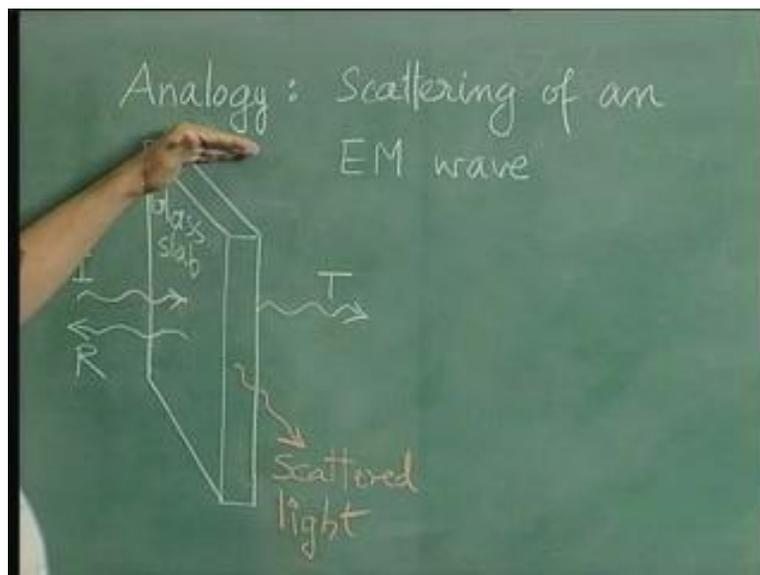
Consider the scattering of an electro magnetic wave in a glass slab. Let us assume that there is a glass slab and you have a viewer who is looking at the glass slab only from this side. So the glass slab uses something like this and light is falling from this side on the slab and you are viewing only at the edge. There is an incident light so you will have

some reflected light and some light will be transmitted. If the glass slab was perfect, that is the refractive index of the medium of this glass slab was exactly uniform then from the side you will not find the glass slab glowing, i.e. you will not be able to detect the presence of the light on the left hand side.

However, in practice our experience is different. When we see the slab from the side we see it glowing which means some light is coming out in this direction which is perpendicular to the direction in which the light is incident. This is because the light is getting scattered so what is coming out of the edge is the scattered light. This scattering takes place because in practice the glass slab has randomly varying refractive index.

Refractive index of the glass slab is not uniform, it is not constant, it is varying randomly. So the medium in which the refractive index is varying randomly scatters an electro magnetic wave which is incident on the medium and which is getting transmitted through the medium.

Exactly the similar way, if you regard the electron wave as analogous to the electromagnetic wave and if you regard the potential variations in the semiconductor as analogous to refractive index of the medium, through which the electromagnetic wave is travelling then you can easily translate whatever we have discussed for the electromagnetic wave to the electron wave. Just as electromagnetic wave is scattered by a medium in which the refractive index is randomly varying an electron wave is scattered by a medium in which the potential is randomly varying.

In fact this randomness of the variation is at the heart of scattering. For example, a phonon scatters an electron because phonon represents randomly varying atomic vibrations which in turn give rise to potential variation which changes randomly in space and time. So this fact must be borne in mind that scattering is a wave phenomenon. Once we understand scattering as wave phenomenon later on we can simplify and treat this phenomenon as a classical phenomenon for deriving equations.