Solid State Devices
Dr. S. Karmalkar
Department of Electronics and Communication Engineering
Indian Institute of Technology, Madras
Lecture - 13
Carrier Transport (Contd.)

This is 13th lecture of the course and the 2nd lecture on Carrier Transport.

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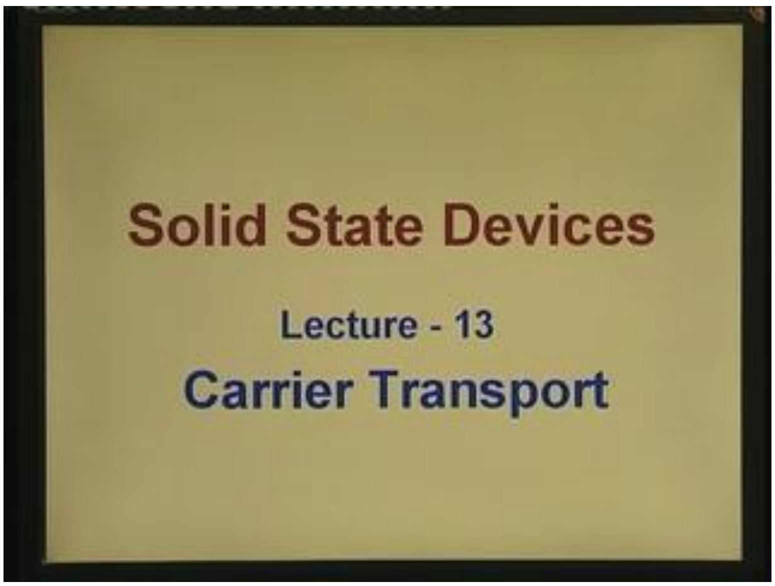

In the last class, we have seen the various modes in which carriers can move in a semiconductor and then we said that we will consider in detail the semi-classical transport. For the semi-classical transport we showed the following.

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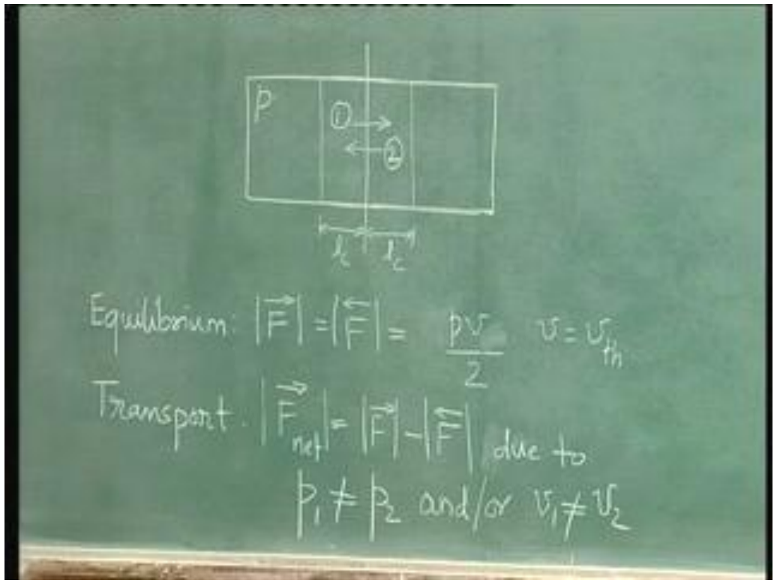

If you take a plane in a semiconductor and observe the flux that is crossing this particular plane from left to right and right to left, then the picture would be something as follows. Under equilibrium conditions the two fluxes are equal and the magnitude is given by $\frac{pv}{2}$ where p is the concentration of carriers. We are considering holes here and here are the velocity of carriers so that is the magnitude of the individual fluxes and since they are equal in magnitude so they cancel each other. Therefore, the particular equation for this flux can be obtained by considering a region of width equal to the mean free path on either side of this plane.

When you disturb this equilibrium, when this is not equal to this then there is difference the net flux and it transports results. This difference can be because of either $p_1 \neq p_2$ that is the hole concentration in this region not being equal to the concentration in this region or it could be because the velocity of carriers which are crossing from left to right not being equal to the velocity of carriers going from right to left that is $v_1 \neq v_2$. This $v_1 \neq v_2$ can be either because of temperature difference between the two regions or because of an application of electric field. So these are the various ways in which the transport can take place. Let us proceed further from here and try to explain this particular curve.

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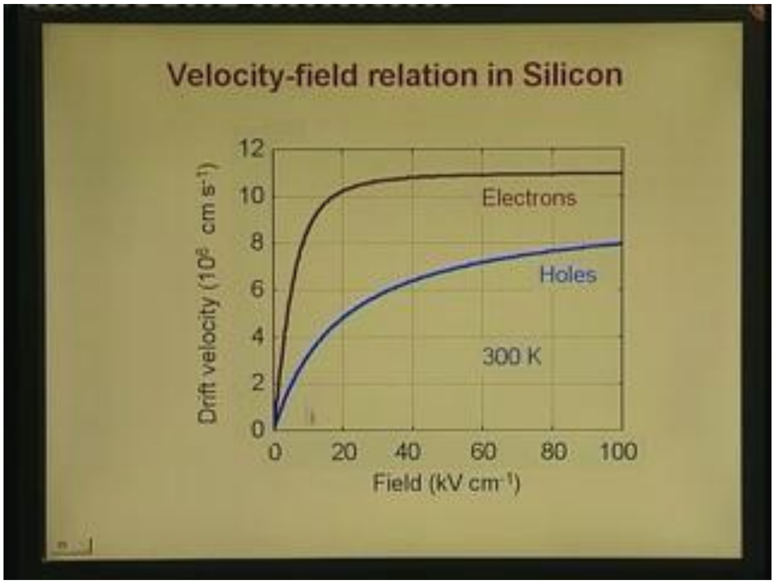

What we will try to do is to show that for small electric field you have a linear dependence between the velocity acquired by the carrier in response to the electric field whereas for large electric fields the velocity is constant.

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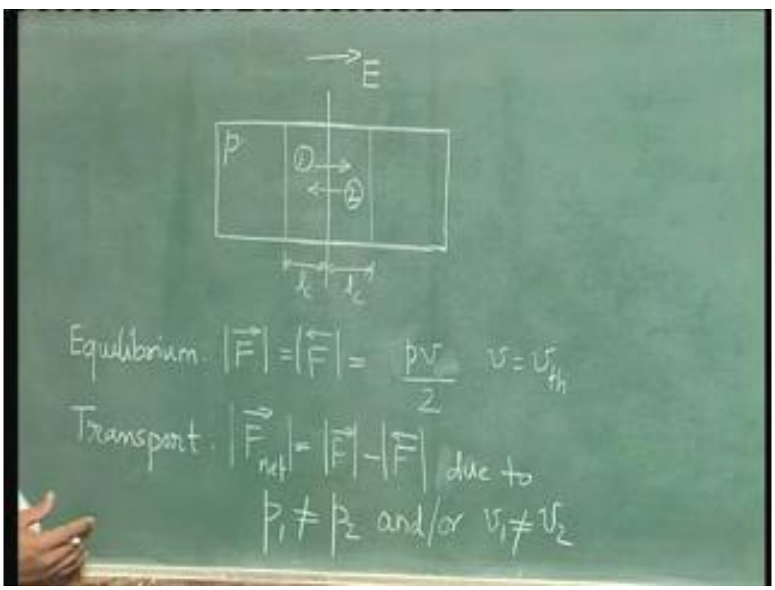

In other words, if we were to translate into this particular model then we will have to show that this net flux increases linearly with the electric field in the case of drift transport i.e. when $v_1 \neq v_2$ the velocities of the carriers which are crossing the plane are not equal because of electric field, that is the drift condition and under that condition the flux will be proportional to the electric field for small electric field whereas for large electric field the flux will saturate and that is what we have to show. The fact that flux will saturate for large electric fields can be seen very easily from here.

Notice that because of the application of the electric field supposing the electric field is in this direction, this electric field aides carriers moving in this direction and therefore the v_1 is increasing or this particular flux is increasing. Whereas the same e opposes the carriers moving in this direction and therefore this flux reduces or v_2 reduces. Now v_2 can utmost be reduced to 0 or this flux can utmost be reduced to 0 you cannot do anything more than that and that is the reason why when the electric field is large and you reduce this particular flux to 0 thereafter there cannot be any change in the net flux even when you increase the electric field.

Then the question arises that if the flux is not increasing when you increase the electric field for large electric fields then what is happening to the extra energy that you are putting in as you increase the electric field.

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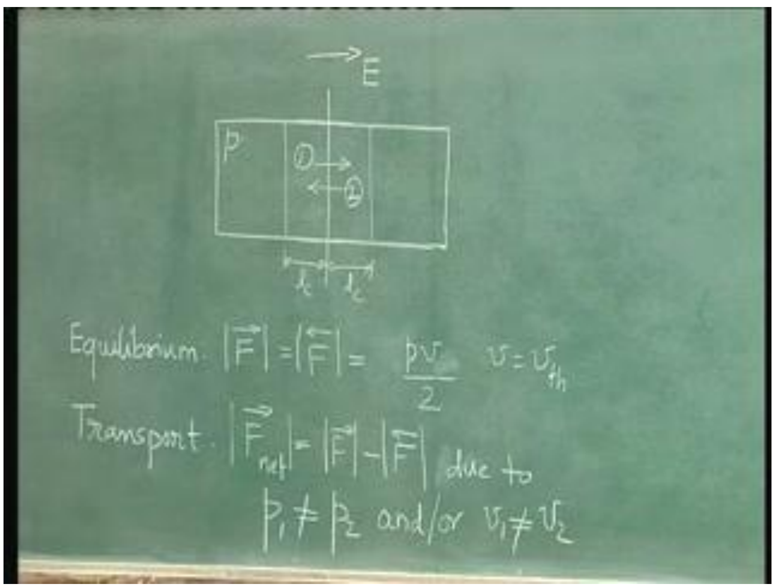

The point to note is that this flux that we are writing here is the directed component it is not the random component whereas the net picture the total picture of the carrier is that it consists of a random component and a directed component. So what happens when the electric filed is large is that on increase of the electric field whatever extra energy you are putting in that energy is going to increase the random component of the carrier motion and not the directed component. So directed component is saturating, the random component is increasing that is what is happening.

Whereas for small electric fields what is happening is that the directed component is increasing linearly with the electric field but the random component is not changing significantly and this is the picture. So let us show the picture for small electric fields, how is it that for small electric fields the flux will increase linearly with electric field for the drift component and similarly for the diffusion component the flux will increase linearly with gradient of the concentration. So this particular topic is called quasi-equilibrium transport i.e. look at the slide.

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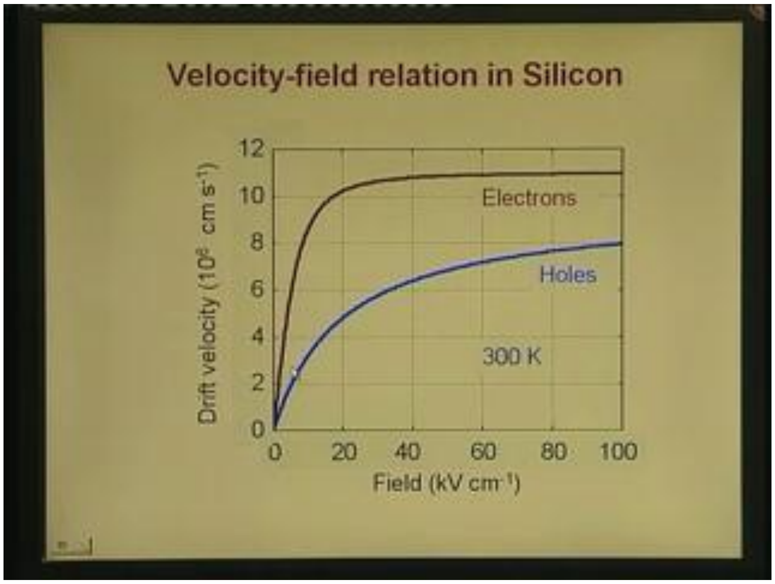

When the electric field is small the disturbance from the equilibrium is small and this condition therefore for small electric fields are referred to as quasi-equilibrium that is a small disturbance from equilibrium.

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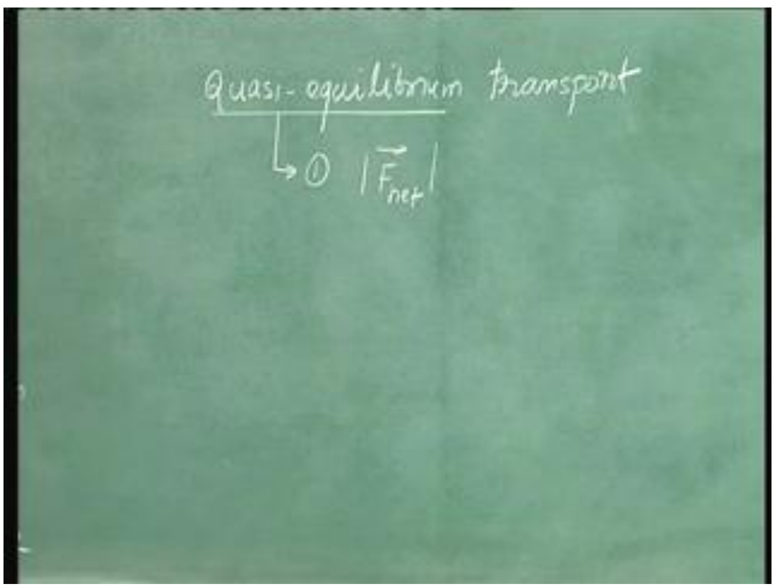

So let us write down what are the implications of the small disturbance from equilibrium. So quasi-equilibrium implies the net flux magnitude which is you note here the difference of these to fluxes.

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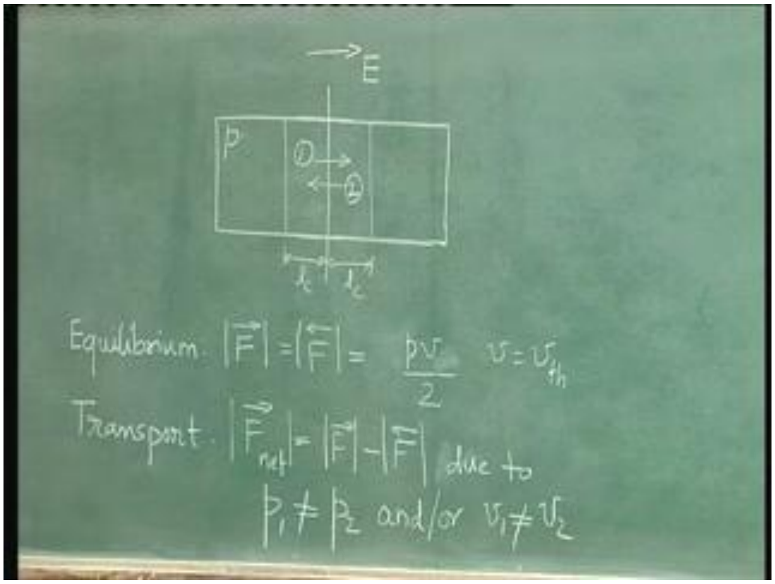

So the net flux magnitude is much lesser than the individual components.

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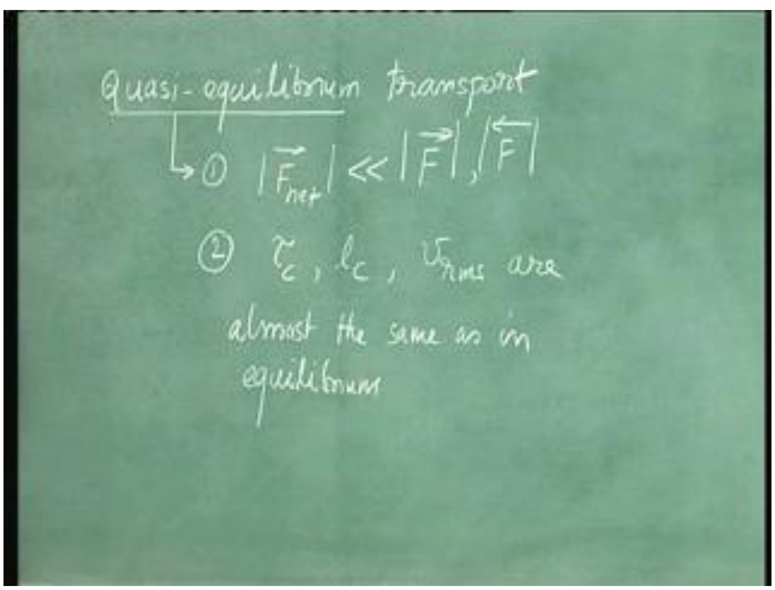

So the difference between the two quantities which are under imbalance is much less than the individual quantities. It is something like saying this quantity is let us say 1000 units and this quantity is 995 units, the difference is 5, so 5 is much less than 995 or 1000 so that is the real meaning of quasi-equilibrium, a small disturbance from equilibrium.

Its second implication of this condition is that the important parameters associated with random motion that is the mean time between collisions, the mean free path and the RMS velocity which is actually the thermal velocity under equilibrium, these quantities are not significantly affected as compared to the equilibrium condition. So these quantities are almost the same as in equilibrium. Under these conditions we need to show that the net flux this particular flux will be linearly related to the driving force. Let us do this for the case of drift, let us come back to this diagram.

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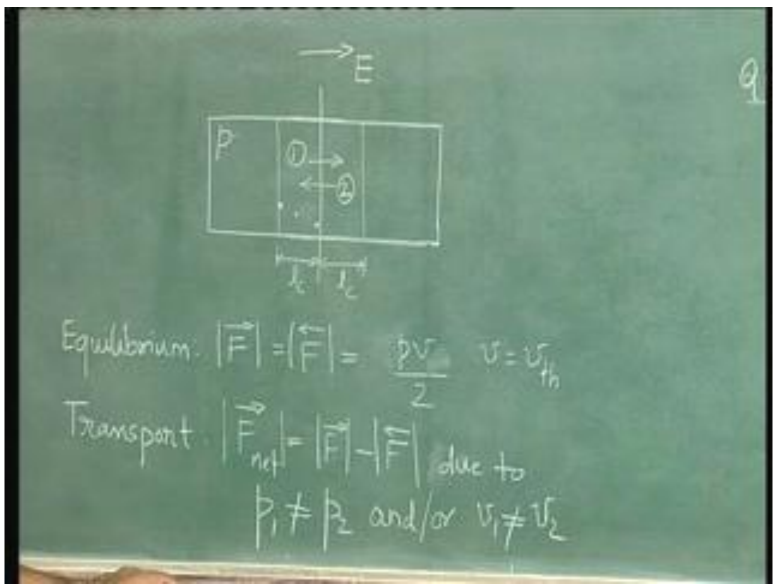

We need to find out what will be this velocity v_1 and the velocity v_2 when you apply an electric field? To calculate the velocity v_1 you can proceed as follows. Supposing you had a carrier here which has just encountered a collision, after the collision because of the electric field it is moving in this direction. And if it is right next to this plane when it is crossing the plane its velocity will be equal to the thermal velocity because it would not be able to gain any velocity from the electric field unless it moves some distance. Only when it is moving some distance then during the motion it is gaining velocity from the electric field.

At the end of collision unless it travels some distance it experiences the field for some amount of time the velocity will not change. So the velocity of this carrier when it is moving to the right is equal to the thermal velocity which is this. But look at a carrier here, if after collision it has started moving in this direction then the next collision it will encounter only after traveling a distance l_c that is just after crossing the plane. This carrier when it moves through a distance l_c will gain a velocity in the direction of the electric field. So let us calculate what that velocity is.

After we calculate that velocity we can take an average velocity for the carriers here which are moving in this direction to be the velocity of this particular carrier while crossing this plane plus the velocity of this particular carrier crossing this plane divided by 2, we can take that as a average because some carrier which is here will travel a distance less than l_c and obviously it will gain a velocity which is less than the velocity gained by this carrier while crossing this plane but that velocity will be more than the velocity of this carrier while crossing this plane. So you have different carriers at different distances from this plane gaining different amounts of velocities.

Strictly speaking the average should be calculated by integration but we will simplify the mathematics and we will simply say the average velocity of carriers in this plane is the velocity that is gained by this carrier while crossing the plane and the velocity gained by this particular carrier while crossing this plane, the average of the 2.

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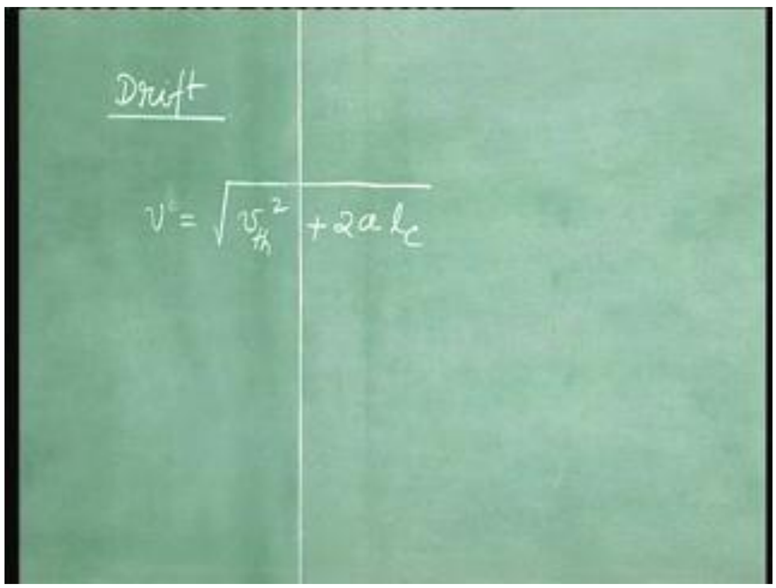

So what is that? The velocity gained by the carrier is when it travels a distance l_c can be written as V is equal to $\sqrt{Uth2 + 2alc}$ where a is the acceleration because of the electric field and l_c is the distance traveled in the electric field.

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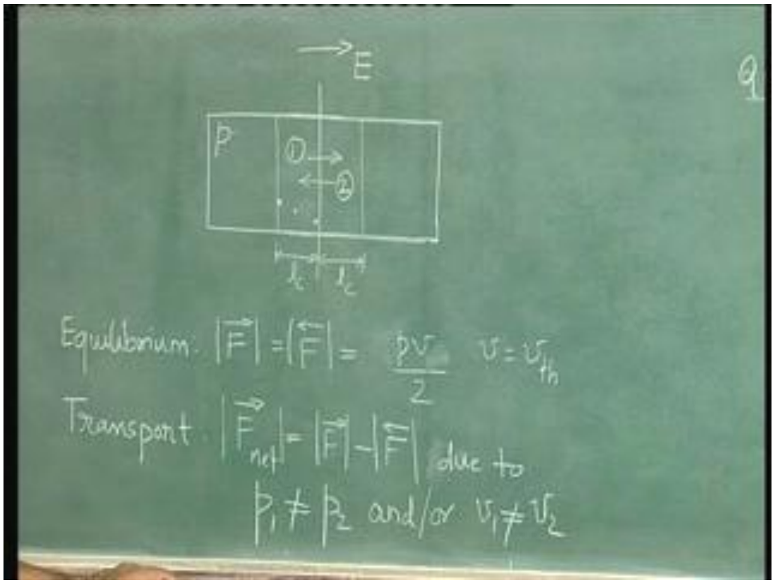

This particular expression applies to this carrier here when it is crossing the electric field it is traveling a distance l_c.

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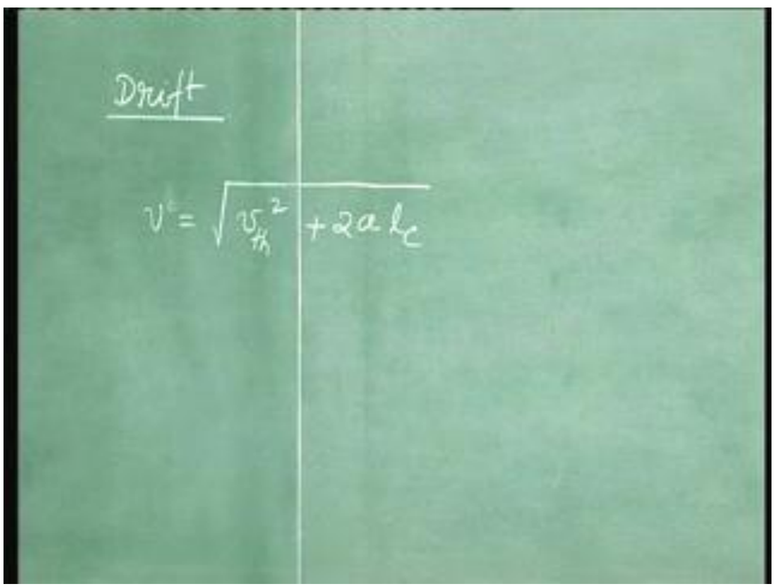

Now let us apply quasi-equilibrium conditions to this particular equation. What is the meaning of quasi-equilibrium?

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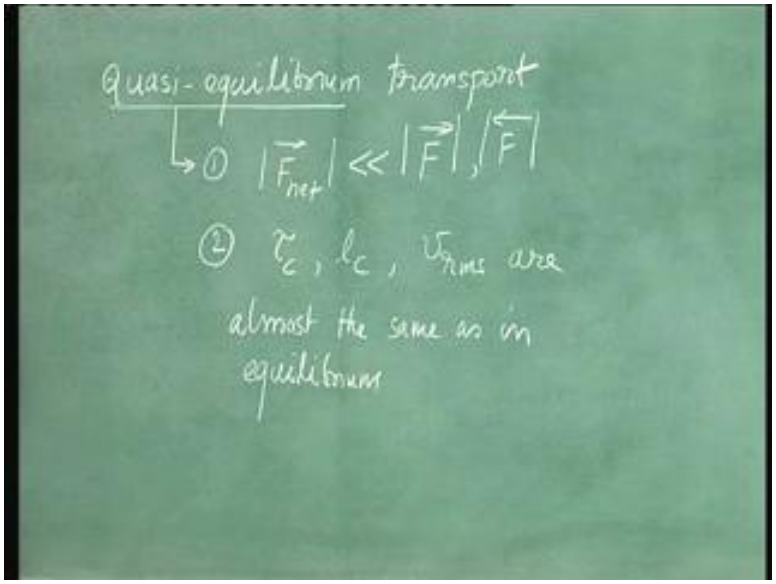

The disturbance is very small so whatever we have listed here for quasi-equilibrium that is the net flux is very much less than individual fluxes which are in imbalance and all these things are not affected.

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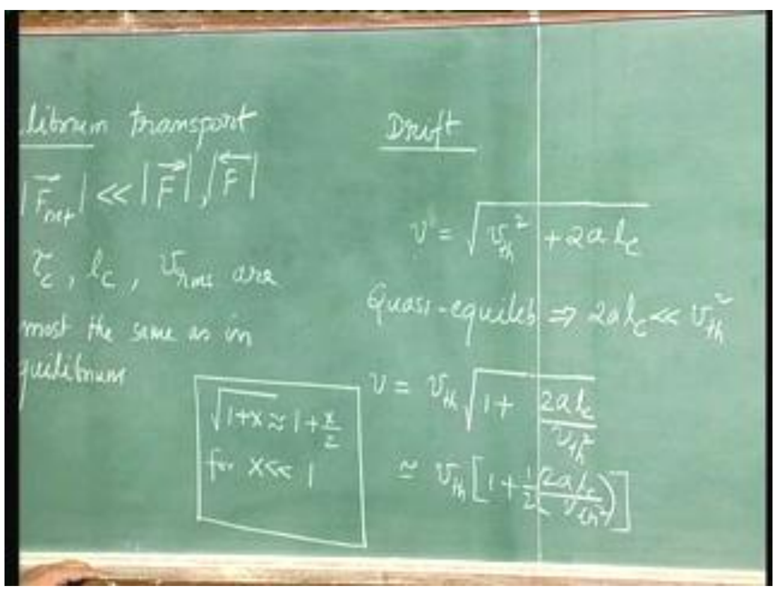

This is equivalent to saying the following: This is the contribution of the velocity due to electric field, this is the velocity because of temperature the random velocity. So this directed component is going to be much less than the random component that is the meaning of Quasi-equilibrium. So Quasi-equilibrium implies $2l_c$ is much less than v thermal square. We can simplify the above as V is equal to $v_{th}\sqrt{1+\frac{2alc}{\ddot{v}th^2}}$ which can be approximated as $v_{th}\left[1+\frac{1}{2}\left(\frac{2alc}{\ddot{v}th^2}\right)\right]$ approximately equal to this. While writing this equation we have used the approximation that $\sqrt{1+x} \cong 1+\frac{x}{2}$ for $X \ll 1$ so we have used this particular mathematical approximation while writing this. Now you can simplify this, you can see that $1v_{th}$ will cancel here with this v_{th} and then the l_c by v_{th} can be written as the tau_c mean free time and these two will cancel with this.

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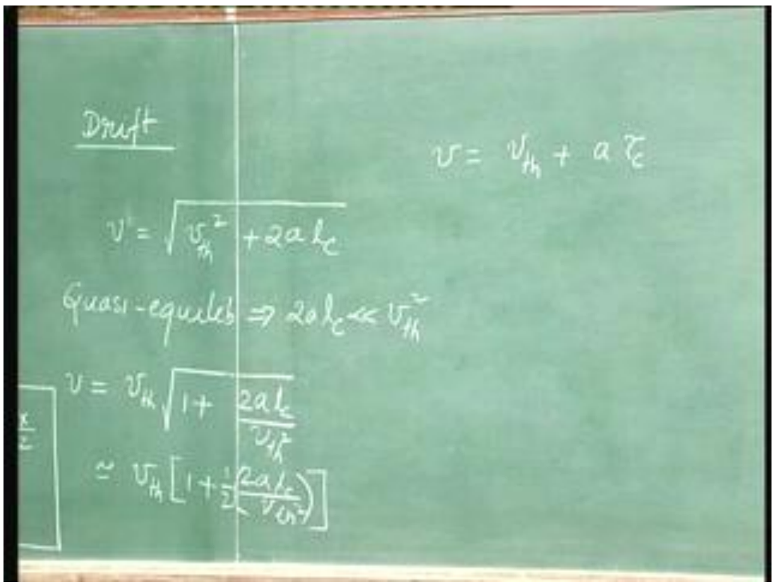

So this quantity can be written as v_{th} plus a tau_c so this is simplification of this particular equation, so this is v. Now we can put an arrow over this as this is the v directed from left to right. We said that the average velocity will be this velocity plus v_{th} by 2, come back to this particular diagram.

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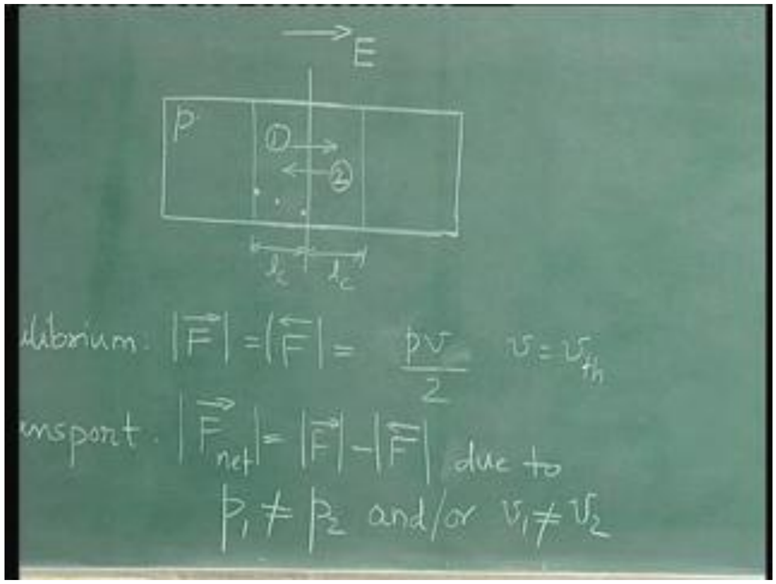

What we have now estimated is the velocity of this particular carrier when crossing this plane. This velocity is v_{th} for this carrier so we must take average of the two so that is what we are doing here and we can write V directed from left to right which is in our nomenclature is v_1 is equal to $\frac{v_{th} + (v_{th} + a\tau_c)}{2}$ is equal to v_{th} plus $\frac{a\tau_c}{2}$ so this is the average velocity of carriers crossing the plane from left to right, so this is the gain because of the electric field the directed motion.

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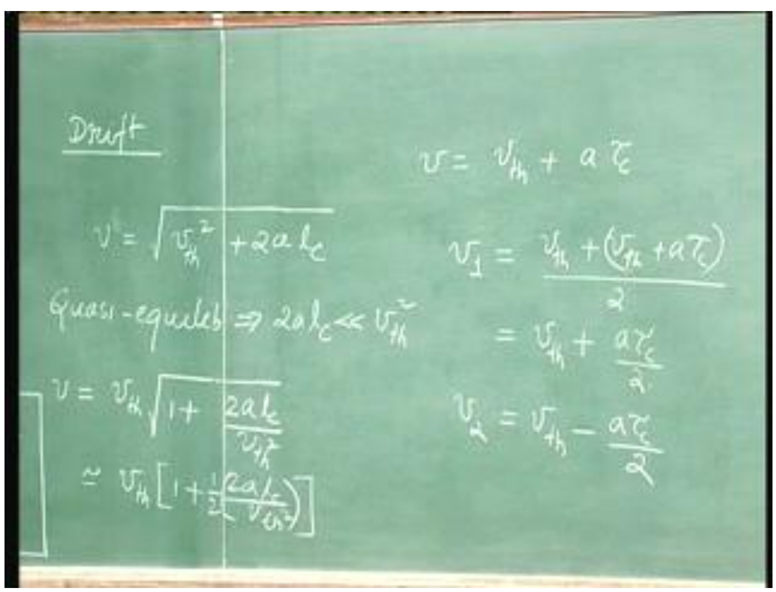

Now we can write expression for v_2 from here v_2 is equal to v_{th} minus $\frac{a\tau_c}{2}$ by a similar analysis because v_2 there is a reduction in the velocity, you can look at this diagram so v_2 is the velocity of carriers crossing from right to left so this electric field is opposing these carriers.

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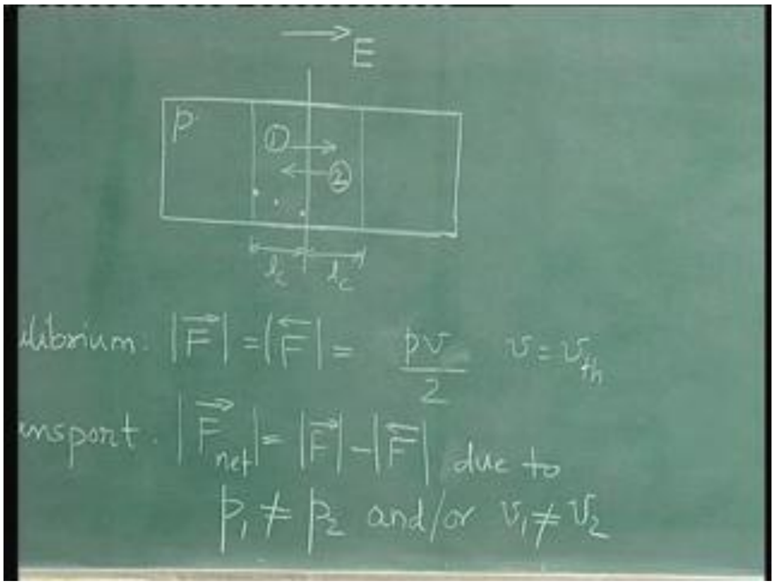

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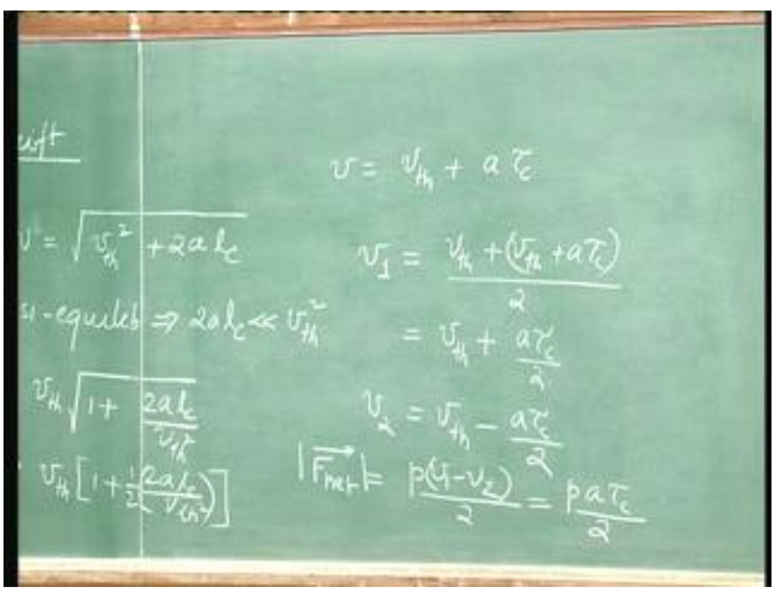

That is why the velocity gain is this in the field or velocity loss. Now we can use the formula that $|F_{net}|$ is equal to $\frac{p(v_1 - v_2)}{2}$ is equal to $\frac{pa\tau_c}{2}$ because these two will get added up and then you divide by two and you end up getting this particular equation $\frac{pa\tau c}{2}$. Now from here we can write the expression for the drift current.

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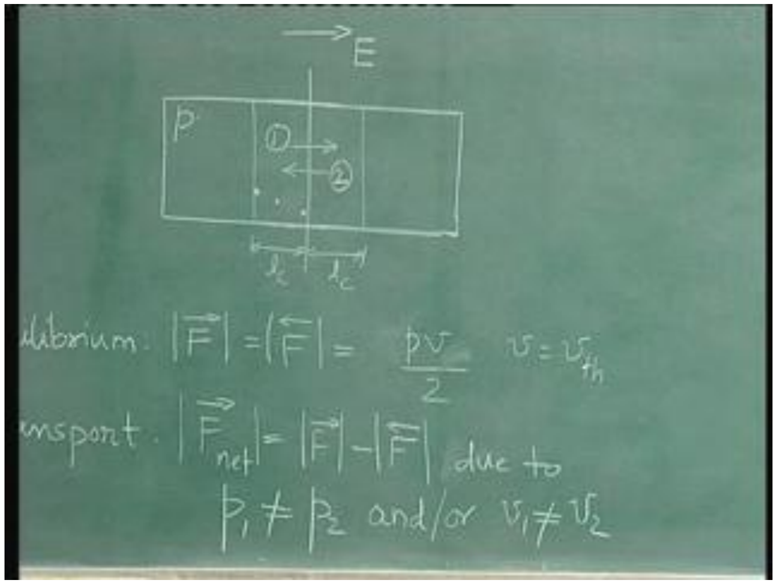

So magnitude of the drift current is J_{drift} is equal to $q|Fnet|$ is equal to $\frac{qpa\tau c}{2}$. We must express this acceleration a in terms of the electric field to get relation between the current due to the electric field.

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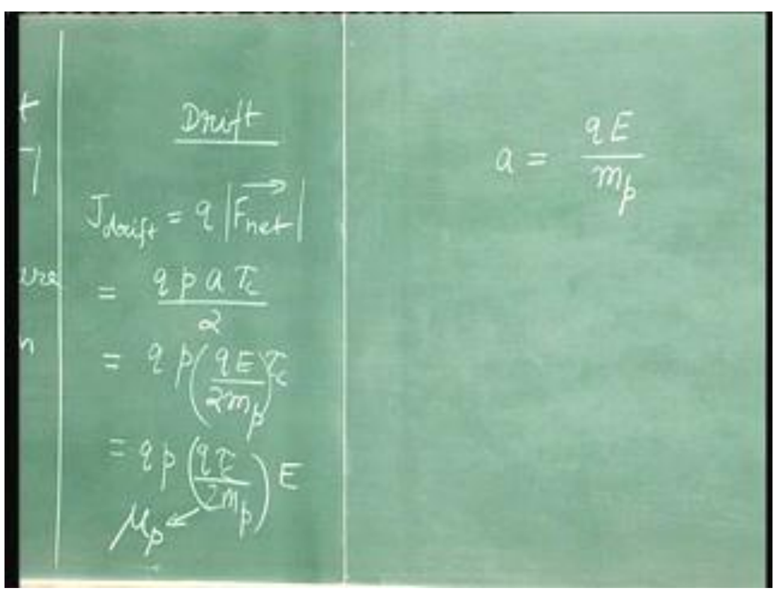

Now the acceleration a we can write as the force on the particle that is a is equal to $\frac{qE}{mp}$ mass of the particle the effective mass. So substituting that here you get this Qp $\left(\frac{qE}{2\text{mp}}\right)\tau c$ which can be rewritten in the form Qp $\left(\frac{qE}{2\text{mp}}\right)E$ that is the current. So what you find is that a current has resulted which it is proportional to the electric field because this is a constant and this constant is called the mobility. Since we are talking of holes this would be called the mobility of holes. If you were to derive a similar expression for electrons it would be mu$_n$ or the mobility of electrons. In the similar way we can derive an expression for the diffusion transport.

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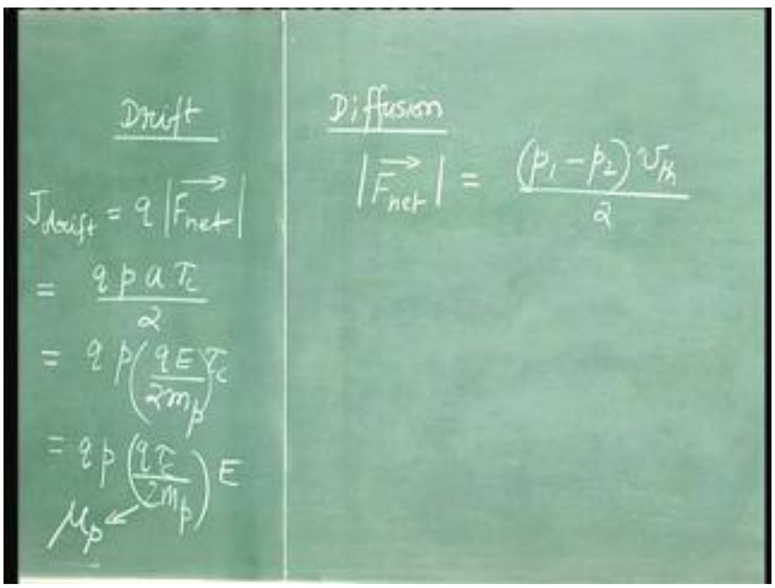

For the diffusion transport the expression is $|\text{Fnet}|$ is equal to $\frac{\text{P(p1}-\text{p2)}\upsilon\text{th}}{2}$.

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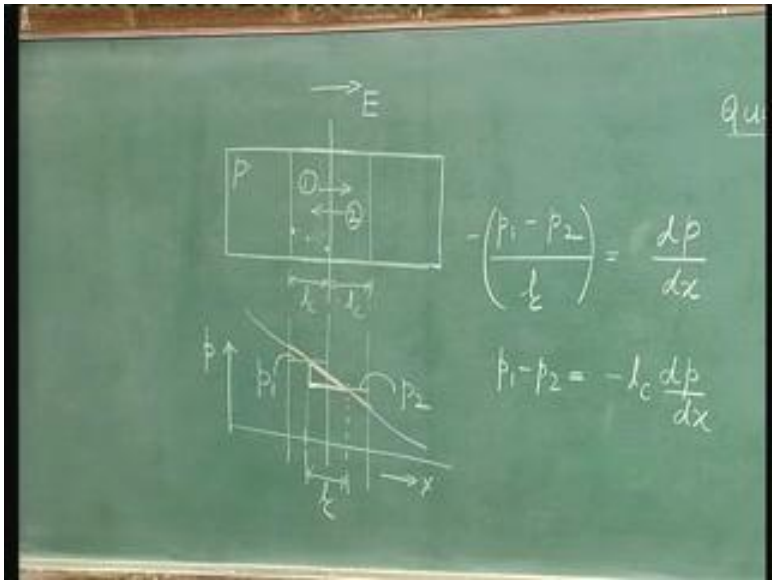

The hole concentration in this region p_1 is different from the hole concentration in this region p_2. And when can this happen? This can happen in the following situation. Let us say the hole concentration is varying as something like this, this is x and in this direction it is p, there is a gradient of hole concentration. On an average the hole concentration here is more than the hole concentration here that is what it means and therefore we need to find out what is the current. How do you find out the current? We need to find out what is the average concentration of holes, you see the hole concentration is changing in this region so we need an average concentration.

If you assume and make an approximation that within this region which is a small mean free path or mean free distance of collision you will recall that this is of the order of 0.1mm so this is really a small width hence we can say even though the concentration will be varying with distance in a non linear fashion may be in general within this small distance we can assume a linear approximation of the concentration.

We can assume that the concentration is changing linearly like this. If we do that then it is very clear that the average of this concentration here would be exactly in the middle, the hole concentration corresponding to middle of this region that is the average concentration for this and similarly the average concentration here. So this is your p_1 and this is your p_2 and the distance between these two points is also l_c because this is half of l_c so this distance is l_c.

Based on this picture now we can write an expression for p_1 and p_2 in terms of the gradient so what can we write? We can write p_1 minus p_2 that is this concentration minus this concentration by that distance so that is this particular slope p_1 minus p_2 by l_c this is l_c the distance is equal to minus dp by dx and notice that the gradient is negative, here p_1 is more than p_2 so p_1 minus p_2 is positive but gradient dp by dx is negative so negative of this negative is this quantity. In other words, dp by dx is negative of this quantity. In other words, it is p_1 minus p_2 is equal to minus l_c d by dx.

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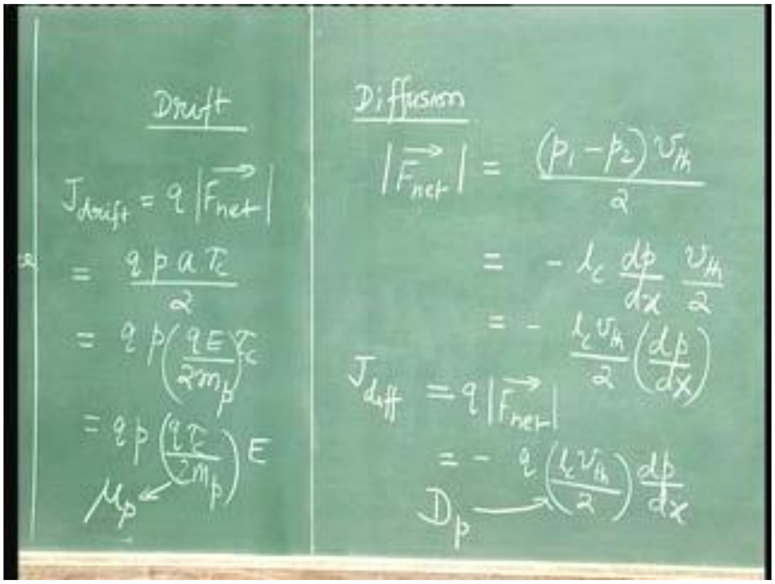

Now we can substitute this result as in this formula we write p_1 minus p_2 is equal to minus l_c dp by dx into v_{th} by 2 that is the net. And by rearranging this you get this is equal to l_c v_{th} by 2(dp by dx) that is the net flux. The current due to diffusion we can write the j diffusion which is directed from left to right, let us only talk about the magnitude, we will remove the arrows and only the magnitude j diffusion is equal to, you multiply this by q as done before q f_{net} is equal to minus q (l_c v_{th} by 2) dp by dx.

In other words, now you can see that the diffusion current is proportional to the gradient of the hole concentration, this is a constant of proportionality and this constant of proportionality is called the diffusion coefficient. In this case we are talking of holes so you put a suffix p to show that this is dp. Now you can compare these two equations. This equation is the equation for drift, e is nothing but the gradient of the potential so I could write e as minus dpsi by dx if you want and then you can see exactly one to one correspondence between these. Let us write down these two equations again to see the exact one to one correspondence.

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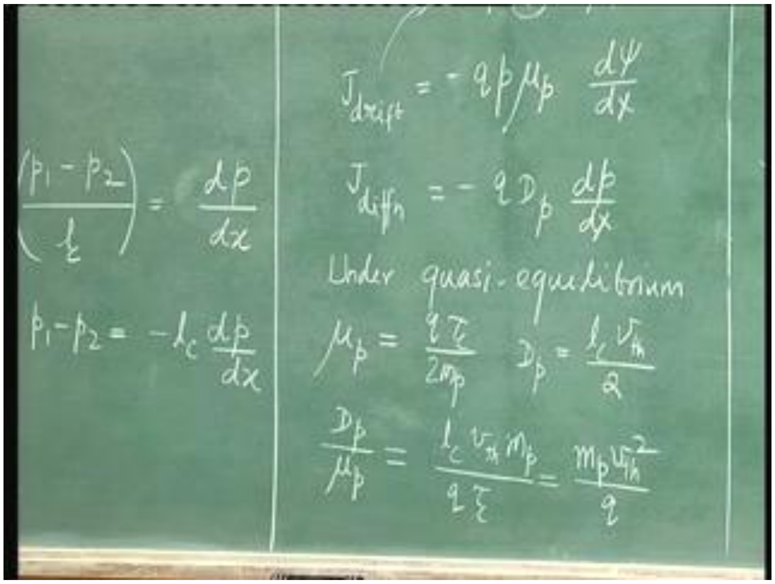

So j drift is equal to qpmu$_p$ into e which is nothing but dpsi by dx where psi is the potential with a negative sign and j diffusion is equal to qdp(dp by dx). So dp is the constant of proportionality for diffusion and mu$_p$ is the constant of proportionality for drift.

Please note that these are applicable under Quasi-equilibrium. And now what these two formulae show. is under quasi-equilibrium the current is proportional to the driving force in both these cases and these are the constant of proportionality mu$_p$ is equal to qttau$_c$ by 2mp and dp is equal to l cv$_{th}$ by 2. So this is how the constants are related to the basic parameters of the random thermal motion, the thermal velocity, mean free distance and mean free time, this is the effective mass.

For example, in the case of drift the velocity of carriers is proportional to the electric field. How do you write the velocity of carriers? You can write the drift current in terms of velocity of carriers. Instead of this particular formula another way of writing the drift current is j drift is equal to q into p into v$_d$ this is the basic definition of current because of any movement q times p into the velocity of the carrier which is the called the drift velocity. From here you find that if you compare these two the drift velocity is given according to this formula mu$_p$ minus (dpsi by dx) which is nothing but e. So vd is mu$_p$e which means mu$_p$ is constant of proportionality between vd and e. So vd is linearly related to e and this is what we saw here in this slide.

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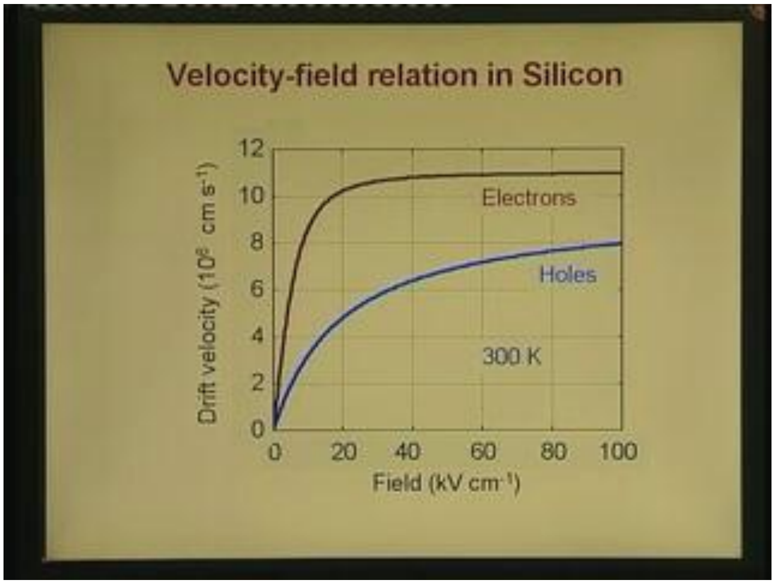

So this is Quasi-equilibrium the small electric field and the velocity is raising linearly with respect to electric field. This is what we have been successful in showing in an analytical manner, we have got an equation. We also have an equation for the constant of proportionality mu_p how much is this?

Next we need to see the relation between these two. Now we can directly see the relation between these two as follows: if I take the ratio dp by mu_p is equal to l_c v_{th} by 2 and these two will cancel. Here you will have q tau_c and mp going up. Now l_c by tau_c is nothing but the thermal velocity, the mean free distance by mean free time is thermal velocity so this is mp v_{th} square by q. Now what is the mp v_{th} square? You can easily identify that this term is related to the kinetic energy of the holes under equilibrium conditions because of random thermal motion, this half is not here, we will shortly see what is the exact meaning of this mp v_{th} square.

We have considered a one dimensional situation here, this is an idealization. In practice the picture is three dimensional. Now, for a three dimensional picture it has been shown that the kinetic energy of carriers undergoing random thermal motion is exactly identical to the kinetic energy of gas molecules in gas under equilibrium at any temperature and that equation is 3 by 2 KT kinetic energy.

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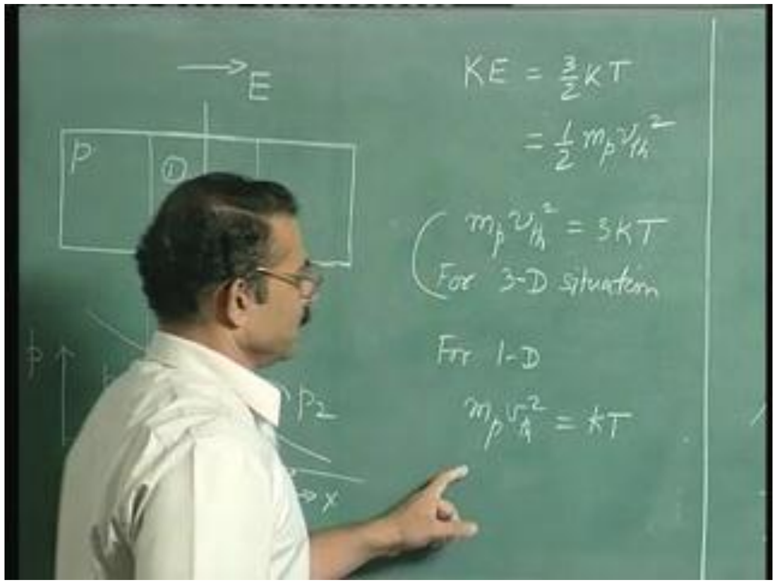

Kinetic energy at any temperature under equilibrium is 3 by 2 KT because of random thermal motion and this is for three dimensional situation. So this is equal to 1 by 2 mp v_{th} square, if you take holes in crystal. So from here we get mp v_{th} square is equal to 3 KT. If you now consider one dimensional situation then your energy that you are writing here instead of 3 KT will become 1 KT so this is for three dimensional situation. For 1D you have mp v_{th} square is equal to 1 by 3 of this, that is KT.

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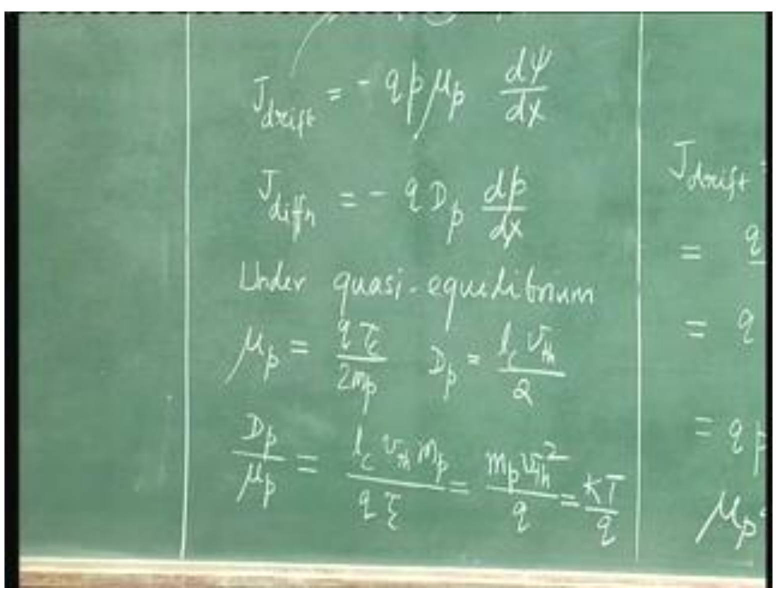

So what you have here the numerator is K times T so this is equal to KT by q. This is a very interesting relation that the diffusion co efficient by the mobility for any carrier where here we have considered holes but you could as well consider the electrons and this ratio is KT by q which is nothing but the thermal voltage. So you have a relation which is called the Einstein relation and that is dp by mu$_p$ is equal to v that is voltage suffix small t.

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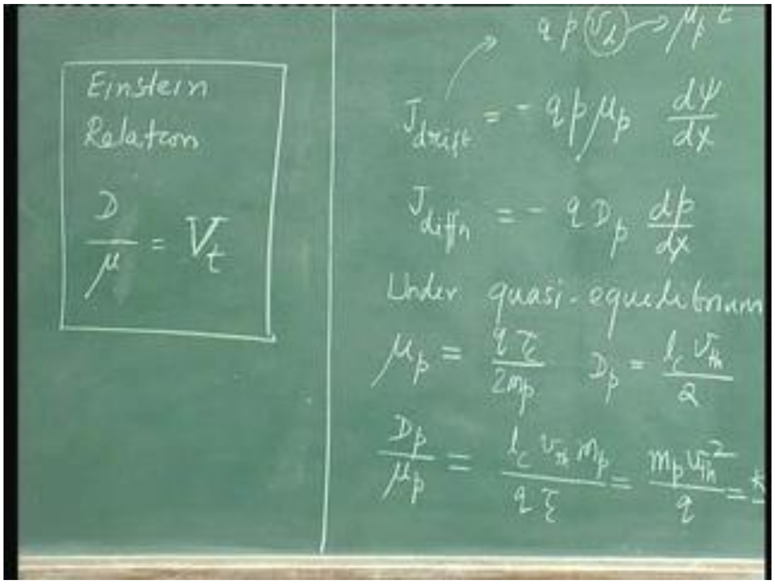

Please distinguish this capital V from small v. So when you write v thermal this is the thermal velocity of carriers or more strictly speaking this is a thermal speed of the carriers because of random motion and this root means square velocity under equilibrium at any temperature. Whereas capital V suffix small t is a thermal voltage. The speed is small v suffix small th so this is a very important relation that is the Einstein relation. In fact we can remove the suffix p because in general this holds for any carrier hole or electron so we will write d by mu is equal to vt. You can put suffix p or n depending on whether it is electrons or holes. It is because of this particular relation that one talks of mobility alone and considers variation of mobility with respect to different parameters and studies or characterizes the mobility.

Once you characterize the mobility which can be done very easily the diffusion coefficient which is a somewhat more difficult constant to characterize then mobility can be readily obtained by this relation at any temperature. You need not consider the diffusion coefficient and mobility characterization separately. You do mobility characterization and from there you can get the diffusion coefficient. Of course you must remember strictly speaking this relation holds under quasi-equilibrium conditions i.e. small disturbances under equilibrium because only under those conditions this formulae that we have are valid.

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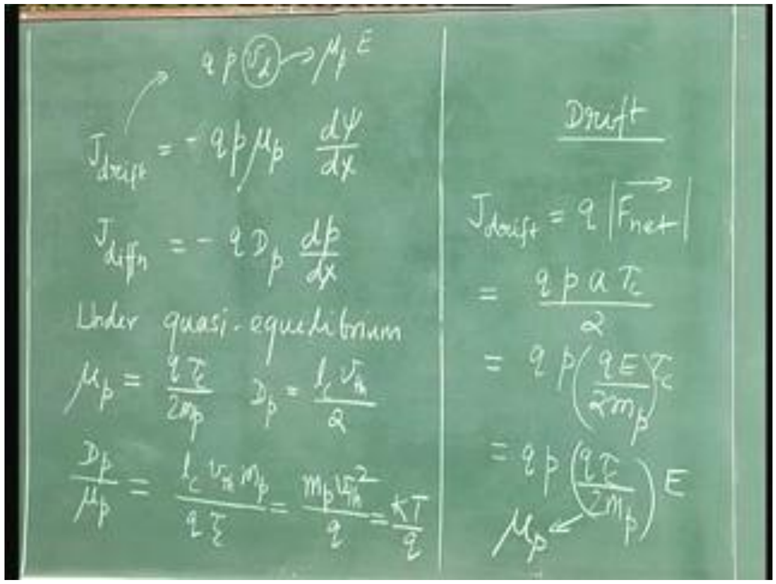

What this Einstein relation shows intuitively is that both drift and diffusion are based on random thermal motion. There is the common basis for both that is why both are related in a very simple manner. Now we will just briefly touch upon the thermo-electric current though we are not going to discuss in detail because thermo-electric current is also based on the random thermal motion like drift and diffusion. What is the situation for thermo-electric current? I will just give the results with out the derivation.

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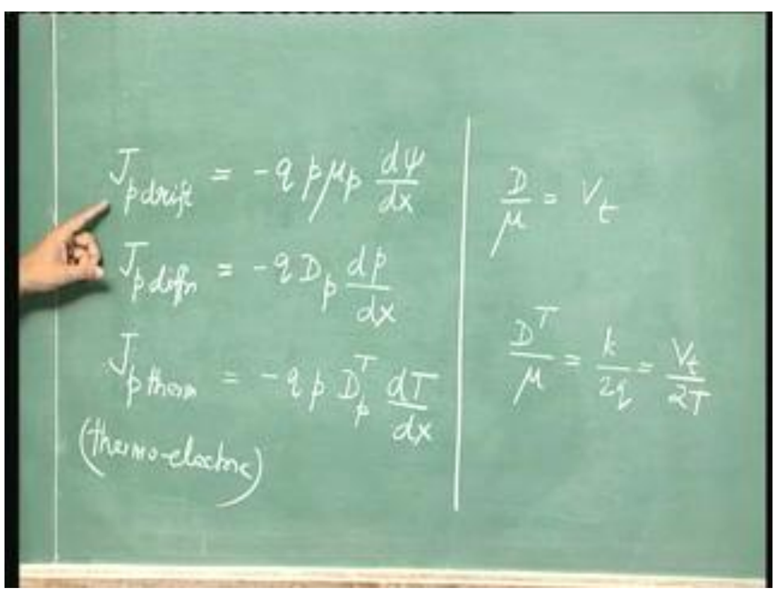

So just as for drift and diffusion you have the current proportional to the driving force that is gradient of the potential here and gradient of the concentration here. For thermo-electric current, I am writing it for holes because for the other two also we had written for holes. One can always write similar equation for electrons. For holes thermo-electric current is given by minus qp the hole concentration into a thermo-electric coefficient same as this coefficient D to the power T to show that this is not diffusion coefficient but a coefficient associated with thermo-electric current. This coefficient is then multiplied by the gradient of the temperature dT by dx. You can see a one to one correspondence between all these three equations.

Now, like you have the Einstein relation d by mu is equal to V_t the relation for thermo-electric coefficient is d by mudT by mu is equal to k by 2q where k is the Boltzmann constant so if you multiply and divide by temperature you will get this relation thermal voltage by 2t. So these two coefficients are also related. In this way you can see the mobility, diffusion coefficient and thermo-electric coefficient are interrelated in a very simple way showing the common basis of random thermal motion underlying this entire transport phenomenon. In fact it is because of this thermo-electric current that you get a voltage between any two contact points which are at different temperatures.

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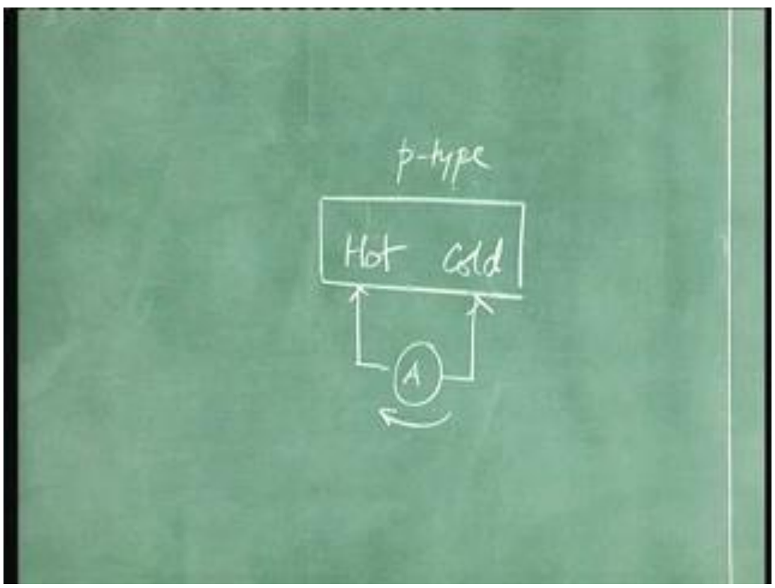

You will recall this particular diagram that we had drawn, hot and cold, and if it is a p-type semiconductor then we said that if you connect an ammeter you will find a current in this direction. Now how do you explain this current in this direction? It is very simple because the temperature here is more than the temperature here the random velocity of carriers here in this region is more than the velocity here which means because of this difference between the velocity v_1 minus v_2 we are assuming that this side is hotter than this side so v_1 minus v_2 is the net velocity.

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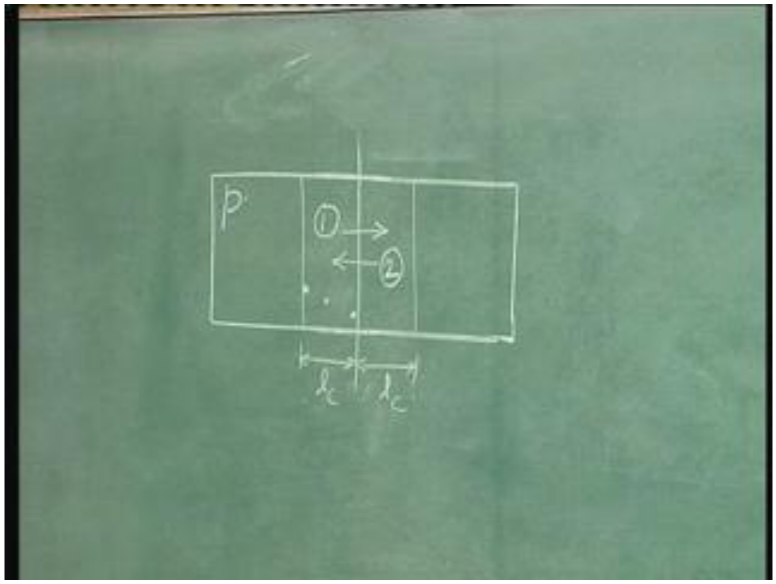

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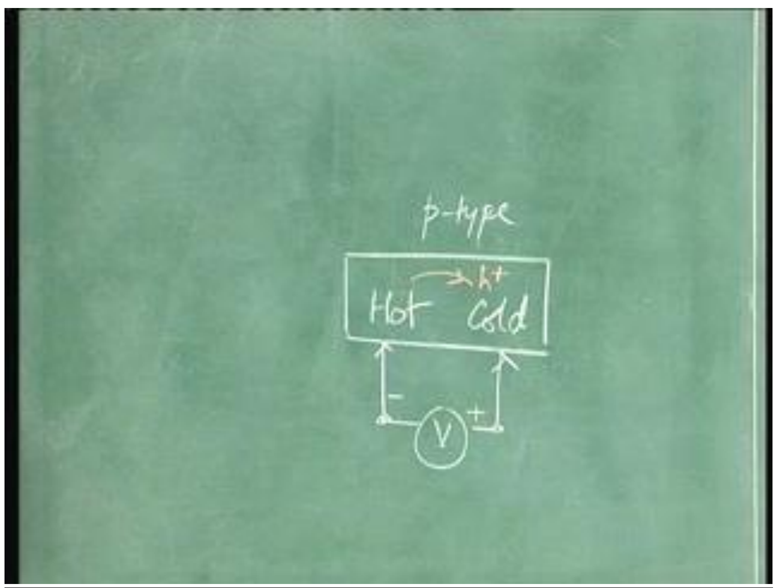

So here the v_1 is the velocity of carriers directed from hot to cold and v_2 is velocity from cold to hot so hot to cold is more hence there is a net velocity a net movement of holes in this direction inside the semiconductor because of thermo-electric current. And when you close the circuit outside you can see that the holes will move this way and then come out and again this is how the current is established when you put ammeter and that is why the current is in this direction. If do not put an ammeter and leave this open circuited then it is very clear from here that what will happen is the holes will tend to accumulate at this point and this point will become positively charged and this point will be negatively charged because this is losing holes and a field will be developed. A potential will be seen if you do not put an ammeter and put a voltmeter. That is, if you stop the current you will see a voltage in this direction. Now that much discussion about thermal electric current is sufficient and if you want to calculate the thermal electric current for small temperature gradients you can use this particular formula.

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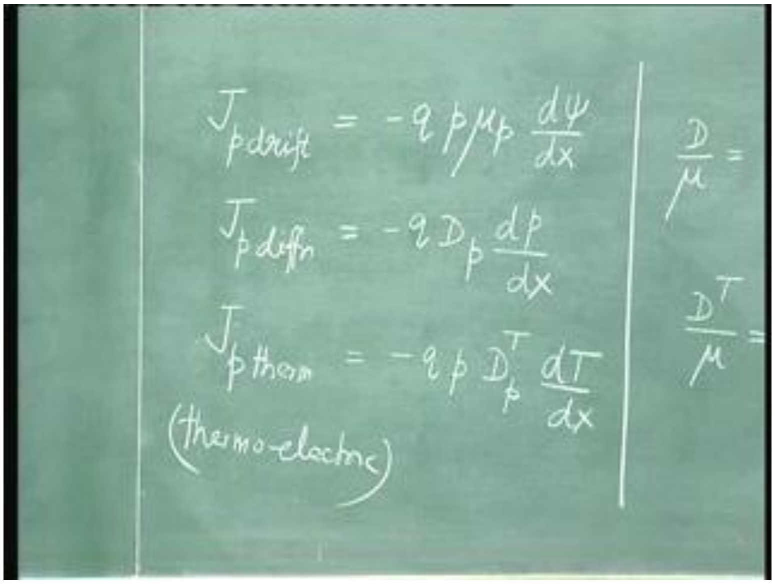

Now a detailed derivation of this formula and the unity underlying these three mechanisms of transport namely drift, diffusion and thermal electric current has been discussed in a publication which is shown on this slide.

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Simple unified elucidations of some semiconductor device phenomena published in IEEE transaction on education, volume 42, on pages 323-327, in the November 1999 issue. So here detailed derivation of all these three currents drift, diffusion and thermal electric current, although they are detailed they are very simple derivations and the relation between them has been clearly shown.

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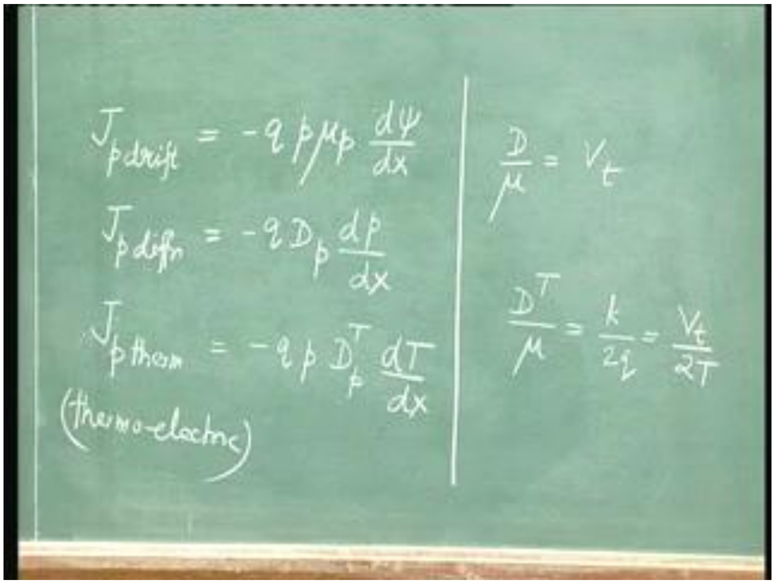

Before we move on to discuss in detail the mobility behavior with doping, temperature and so on let us recall mobility through these relations here namely diffusion coefficients and thermal electric current coefficients and get more information on them. That is why we need to discuss mobility alone in detail, it can be characterized easily. Before we get into this discussion let us understand clearly the fact that in response to the electric field in drift transport you are getting a constant velocity and not acceleration, this point needs to be emphasized.

And similarly for diffusion transport also in response to a concentration gradient you are getting a constant velocity of the carriers i.e. the velocity is not changing with time. Now in the case of drift motion this can be somewhat perplexing though we have made a derivation still a doubt can remain like how are you getting a velocity that is constant with time in response to electric field, let us consider the movement of electrons in vacuum and whatever we are saying for electrons the same applies to holes, since we are considering the vacuum we consider electrons because holes cannot exist in vacuum and that is why we are considering electrons.

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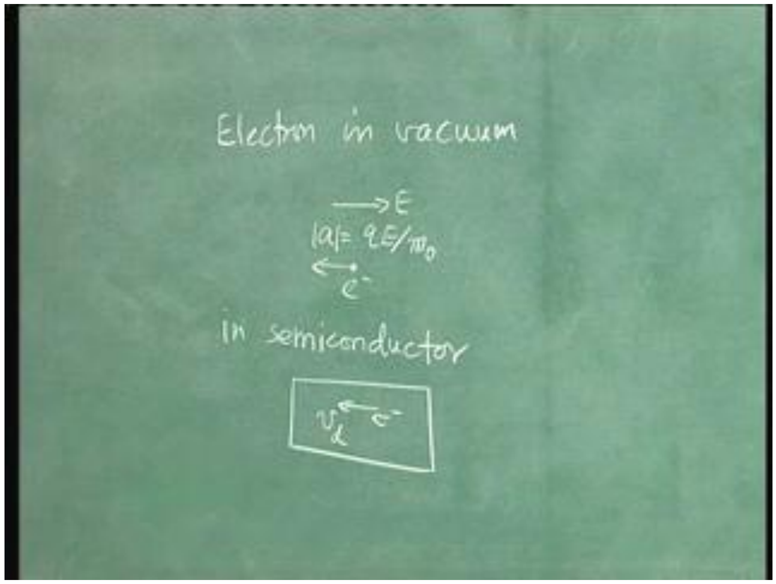

So take an electron in vacuum, if you apply an electric field e it will move in this direction and it will acquire a constant acceleration, it does not acquire a constant velocity but it acquires a constant acceleration which means its velocity will go on increasing with time.

In contrast to this in a semiconductor crystal what is happening is that when you apply the same electric field in semiconductor in this direction here also the electron moves but here its results in a drift velocity, a constant velocity of carriers rather than the acceleration which means the velocity is not changing with time so here it is an acceleration a is equal to qe by m_0 mass of the electron this is in vacuum so m0 is the magnitude of the acceleration for the electron and here it is a uniform velocity, how is this possible?

Please note the differences in these two cases, in the semiconductor you are having other particles surrounding the electrons and the electron is being scattered that is why it is undergoing random thermal motion. Here there is no such random thermal motion so it is because if this random motion that the electron is not able to continuously accelerate because of the other particles present around the electron. The electron is encountering friction during its movement and because of this friction or opposition from the other particles. It can only acquire a constant velocity and its velocity cannot increase with time so the analogy for this is as follows.

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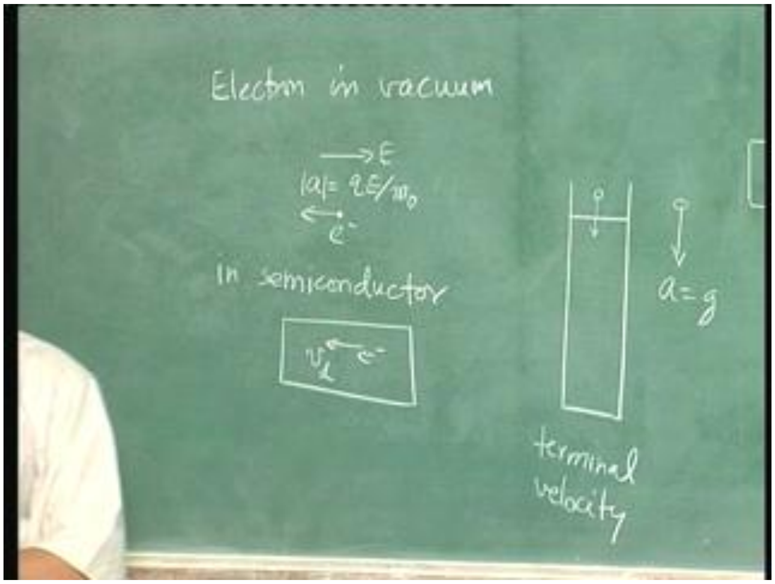

Let us do this experiment which you would have done in your Physics class, if you have a jar of fluid, and this is the fluid and if you drop a steel ball in this you know that after traveling some distance the steel ball acquires a uniform terminal velocity. So, because of gravity it does not go on accelerating, if it is in a viscous medium which opposes the motion of the ball which is causing friction if the same ball is outside there is acceleration a is equal to g it is accelerating continuously whereas if the same ball falls in a viscous medium then it acquires a uniform terminal velocity. Same is the situation for the electrons, within a crystal it acquires a uniform drift velocity in response to electric field so this should not be difficult to appreciate. Now we will move on to discuss how the various scattering phenomena affect the mobility and how the mobility varies with doping and temperature.

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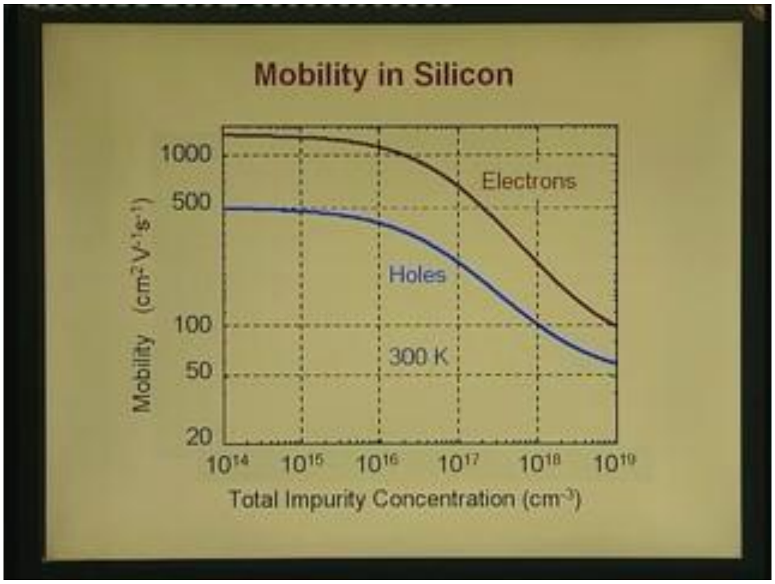

In other words, we want to discuss about these graphs.

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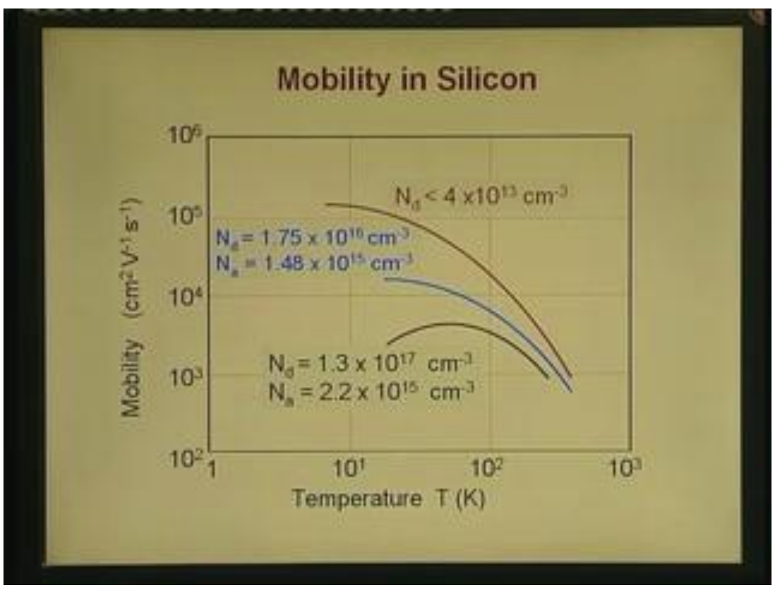

Mobility variation with total impurity concentration is shown here. The decrease in mobility and mobility variation with temperature as well as doping is shown in this particular slide. They are the graphs for which we want to give a qualitative explanation a theory and some kind of expressions.

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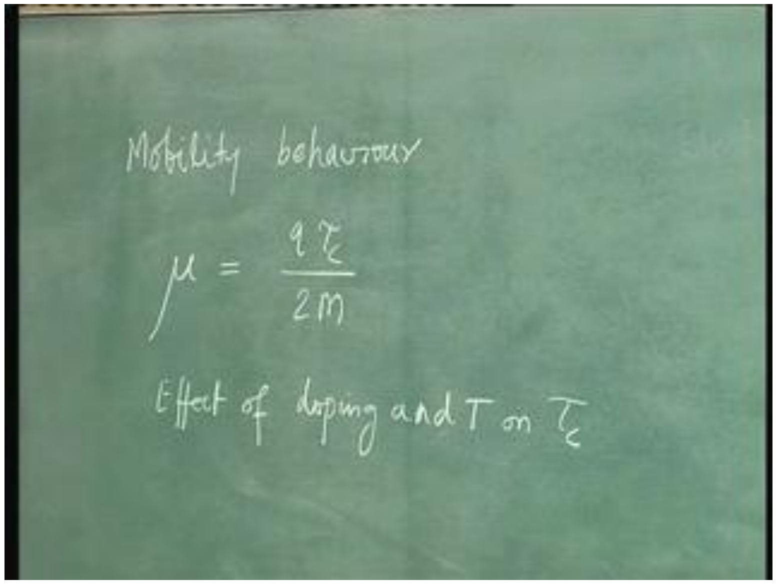

We can derive this information from the formula for mobility. The formula for mobility is q tau$_c$ by 2m where suffix for m can be either n or p. It can be either electrons or holes it does not matter what it is, this is the general expression for mobility. If you want to know how mobility is affected by doping and temperature essentially it falls down to finding out how this particular term that is the mean free time between collisions is affected by doping and temperature. So, effect of doping and temperature on tau$_c$ is what we want to see.

In other words, what we want to see is how the number of scattering events in a unit time is affected when you change doping and temperature. Now, for this purpose we need to appreciate the fact that when you change the temperature you are changing the phonon concentration and if the temperature is very high you can also change the minority carrier concentration. So temperature can affect the carrier concentration and it can affect also the phonon concentration. On the other hand, the doping does not affect the phonon concentration so long as the doping is moderate since the crystal structure is not affected so doping only affects the carrier concentration. So what are the scattering phenomena we need to discuss?

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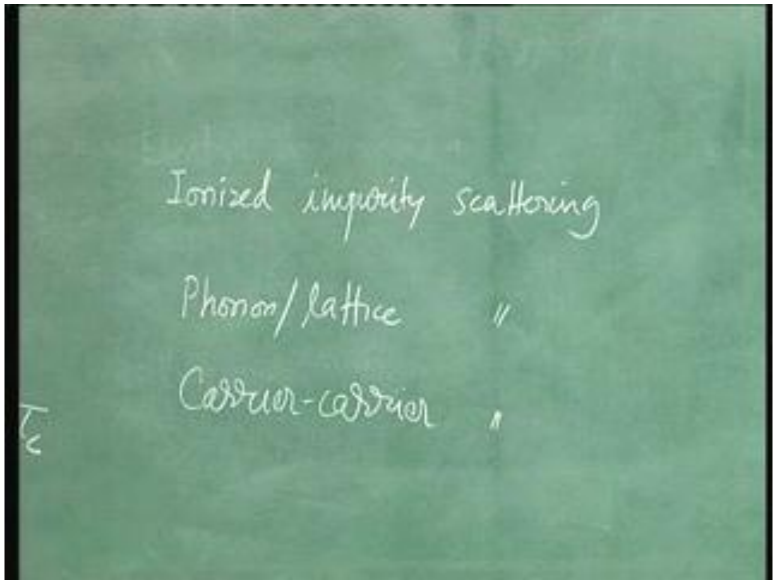

The scattering phenomena as we know are ionized impurity scattering then the phonon or lattice scattering and then carrier-carrier scattering because apart from the carrier which is moving you have other particles namely ionized impurities phonons or vibrating lattice and other carriers so the carrier collides with these things. Let us take up these phenomena one at a time. In other words, what we have going to do is we are going to see how the tau$_c$ is going to be affected by each of these assuming only one type of scattering phenomenon is present then we will combine this information by superposition. So first let us take up the ionized impurities scattering.

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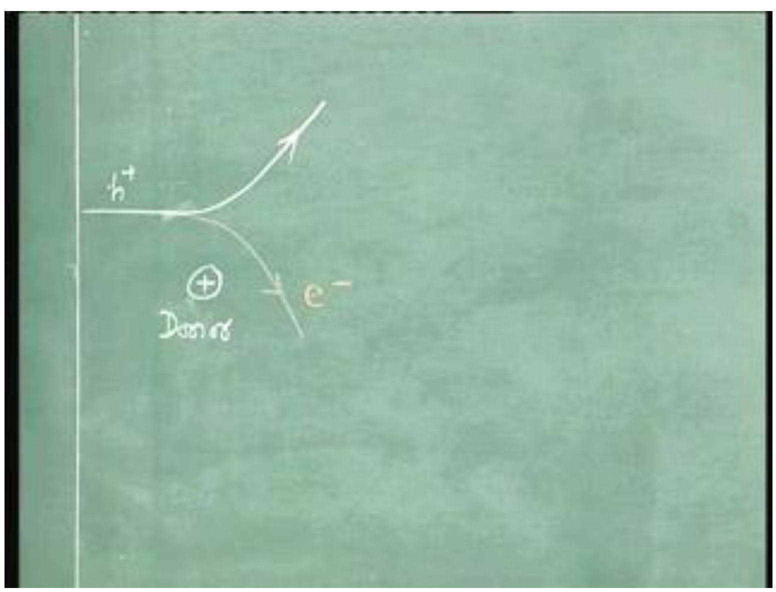

As we discussed the ionized impurities scattering results because of change in the direction of motion of a carrier. Supposing this is an ionized donor and if a hole is moving in this direction as it comes near the impurity it gets repelled and it will move in this direction so this is the scattering of the hole by the impurity.

Similarly you can have scattering of the electron. If the electron were moving here it could move in this direction this is for electron and this is the donor, instead of nd I will put donor because nd is a concentration so this is a donor impurity. Similarly one can draw for an acceptor impurity the picture the scattering. This change in direction of this particle is taking place because of the force of attraction or repulsion between the particle and this particular charge. Obviously the extent of change will depend on how much time the particle spends in the vicinity of this particular charge. If the velocity of the particle is more the velocity with which the particle approaches this charge is more then obviously you expect that it will not bend that much.

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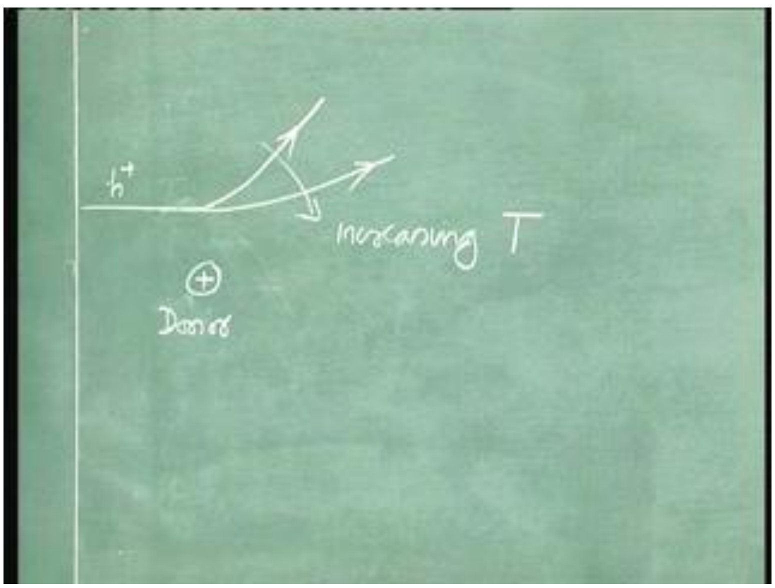

So we are talking about holes, for simplicity you can always do that for electrons, if the velocity is more the path would be something like this it will not bend that much because in the vicinity of this particular charge it will spend less time it is moving much faster so this is increasing particle velocity or speed. Now as you increase the temperature the random velocity of charge increases that is these carriers increase.

Therefore we can say this is picture for increasing temperature. So with an increase in temperature the scattering will be less because of ionized impurities. On the other hand, it is also clear from here that if more the number of ionized impurities greater is the chance of the carriers getting scattered so it does not whether you have the donors or acceptors because both donors and acceptors will scatter the particles so higher the concentration of impurities higher is the chance of scattering. From here we can derive the following information for ionized impurity scattering.

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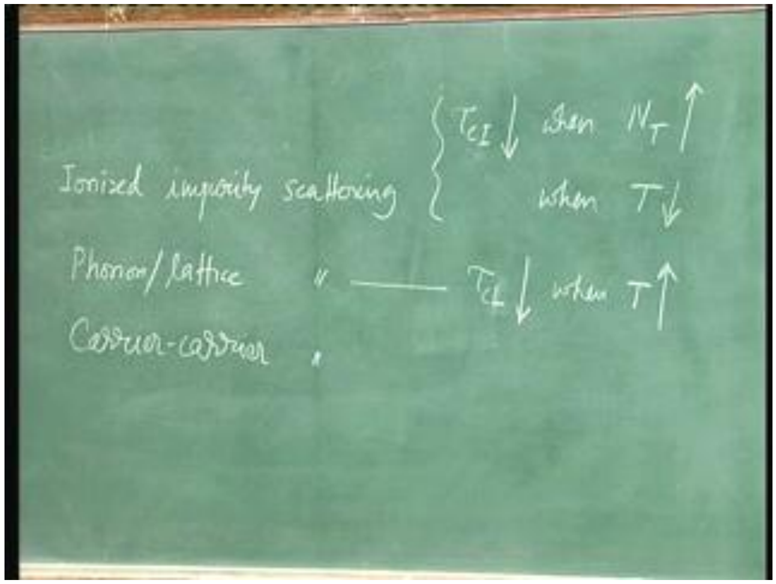

That is, the number of scattering events is more or tau_c we will put a suffix I to show that we are talking of ionized impurity scattering. So tau_c corresponding to I ionized impurity will fall as the number of ionized donors or acceptors increases. This we shall represent as total ionized constant impurity concentration nt where it should be understood that this corresponds to ionized impurities that is why the plus and minus signs are important. So as nt increases so tau_{cI} falls when nt plus na minus increases.

Or as a function of temperature if you want to see the scattering is more at lower temperatures that is what this shows. At high temperature the scattering is less which means the scattering is more at lower temperatures. This is for ionized impurity scattering tau_{cI} falls when total ionization impurity concentration increases or when temperature falls. So please note fall in tau_c I means increased scattering so more scattering means time between collisions will be less.

Now one can similarly consider the situation for the phonon or lattice scattering. It is very clear that as the temperature increases this scattering will be more. For this we can write the tau_{cL} here L stands for lattice or phonon scattering tau_{cL} falls or scattering is more when temperature raises this is for lattice scattering. Therefore what about carrier-carrier scattering? For carrier-carrier scattering we must consider scattering of electrons by electrons and scatter of electrons by holes, similarly scattering of holes by electrons and scattering of holes by holes. We can divide these four events into two types: That is scattering of a particle by particle of the same polarity and scattering of the particle by particle of the opposite polarity.

Consider scattering of the particle by particle of the same polarity. If one electron is colliding with another electron it will transfer its momentum and energy to the other electron. Since the current is not going to be affected because current is the result of the energy and momentum of the entire population.

Since the energy and the momentum is conserved the collisions between particles of the same type does not affect the momentum of the entire population and in any direction. This means therefore the directed component of the momentum will not be affected, the component which is causing the current so one electron collides with another electron or one hole collides with another hole since it transfers the momentum and the momentum remains in the same direction there is no effect on the current, so current is not affected it does not reduce.

Therefore the carrier-carrier scattering is not important for carriers of the same polarity but scattering by carriers of opposite polarities definitely affects the current. And this point we shall consider in the next class in detail as to how scattering of electrons by holes affects mobility of electrons and how scattering of holes by electrons affects the mobility of holes. This particular phenomenon of scattering we shall consider in the next class in detail and then we will also summarize or rather put together the picture because of all these three mechanisms of scattering and from there we will get the behavior of the mobility as a function of temperature and as well as a function of doping.