Semiconductor Device Modeling
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Lecture – 04
Semi-classical Bulk Transport: Qualitative Model

Let us start with what we did in the previous lecture, so we mentioned the various mechanisms of carrier transport particularly semi classical carrier transport which we want to explain and for which we want to develop a model. So, we mentioned about drift diffusion, thermo electric currents then we talked about velocity saturation, negative resistance, velocity overshoot and Ballistic transport.

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Module 2

Semi-classical Bulk Transport:

Qualitative Model

Bulk of a Large Semiconductor

Under Equilibrium

Then, we began qualitative modelling of these transport mechanisms. The first step was to model the equilibrium under; the model semiconductor under equilibrium. So, that is what is the topic of lecture today also, bulk of a large semiconductor under equilibrium. In the previous lecture, we mentioned about the particle approximation. We said that we will regard the semiconductor as consisting of particles namely electrons, phonons, holes and photons hovering about randomly around fixed impurity atoms located in random locations.

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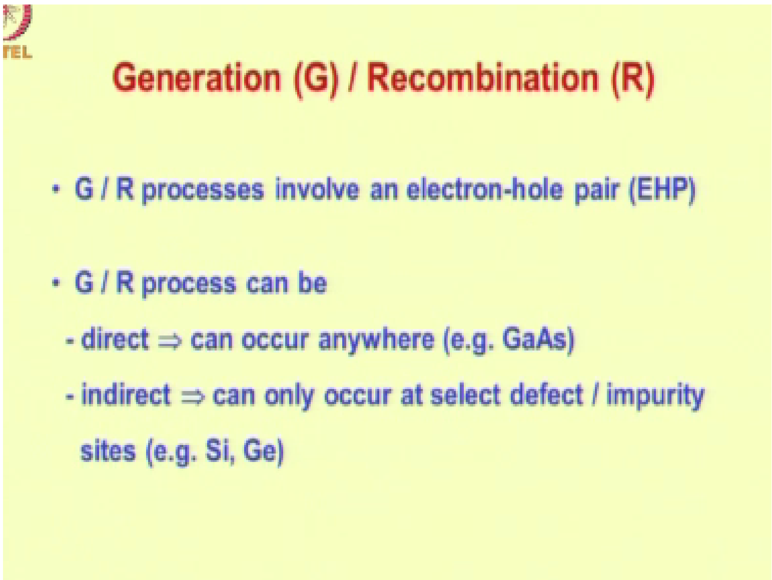

Generation (G) / Recombination (R)

- G / R processes involve an electron-hole pair (EHP)
- G / R process can be
  - direct ⇒ can occur anywhere (e.g. GaAs)
  - indirect ⇒ can only occur at select defect / impurity sites (e.g. Si, Ge)

Now, the next important thing that we should mention about semiconductor equilibrium is generation recombination processes. We will abbreviate generation by G and recombination by R, so generation recombination processes involve an electron hole pair. So, when we talk about generation we are talking about generation of an electron hole pair. When we talk about recombination, we are talking about recombination of an electron hole pair.

Now, where can the generation recombination process take place? Now, there are 2 types of generation recombination processes. A generation recombination process can be direct or it could be indirect. A direct process is one which can occur anywhere, for example in Gallium arsenide. The indirect process on the other hand is one which can only occur at select, defect or impurity sites as it happens in silicon or germanium.

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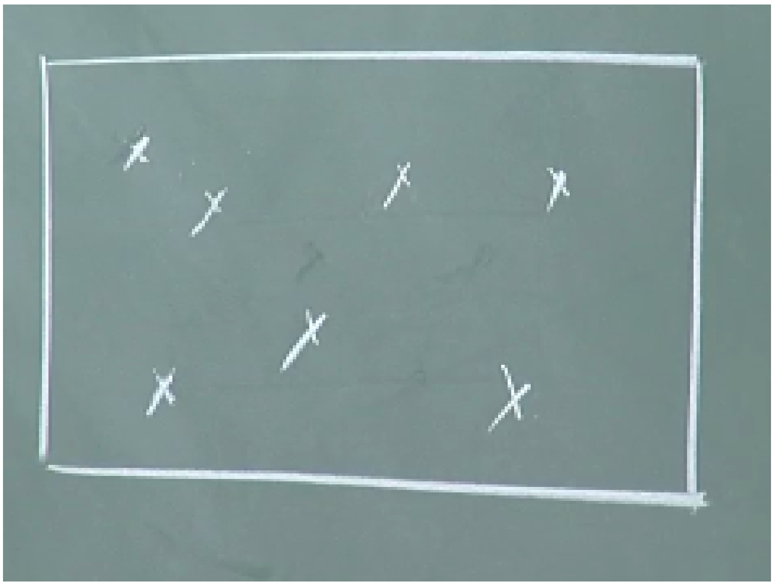

To explain that pictorially, suppose this is a semiconductor sample and wherever an electron and hole meets, recombination can occur then it is called direct. Now, this is the kind of situation in Gallium arsenide. On the other hand, in silicon, there are some locations where you have defects or particular type of impurity sites, they are called deep levels. So, only at this select impurity sites or defects, if an electron and hole meets then recombination can occur.

So, this is an example of, this is how indirect recombination occurs. So, we can link the direct and indirect recombination to the nature of the band gap, right; direct band gap and indirect band gap. Now, this was also done in the first level course, we will mention here that usually in semiconductors where direct recombination dominates, the recombination rate is high because it can; recombination can occur anywhere.

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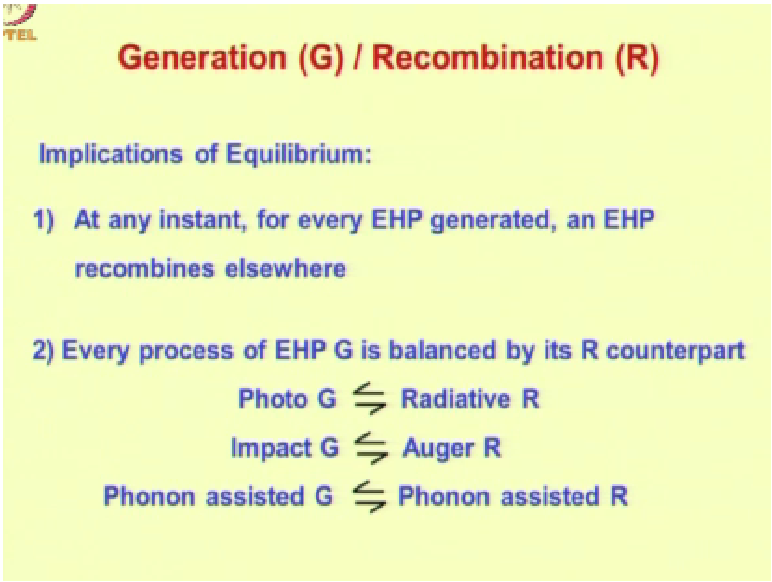

Generation (G) / Recombination (R)

Implications of Equilibrium:

1) At any instant, for every EHP generated, an EHP recombines elsewhere

2) Every process of EHP G is balanced by its R counterpart

Photo G ⇋ Radiative R

Impact G ⇋ Auger R

Phonon assisted G ⇋ Phonon assisted R

On the other hand, in semiconductors where the recombination method is indirect since it can only happen at select sites, which have deep impurity levels, the recombination rate is less. So this is natural. The next point about generation recombination; what are the implications of equilibrium? So first implication is that at any instant for every electron hole pair generated and electron hole pair recombines elsewhere.

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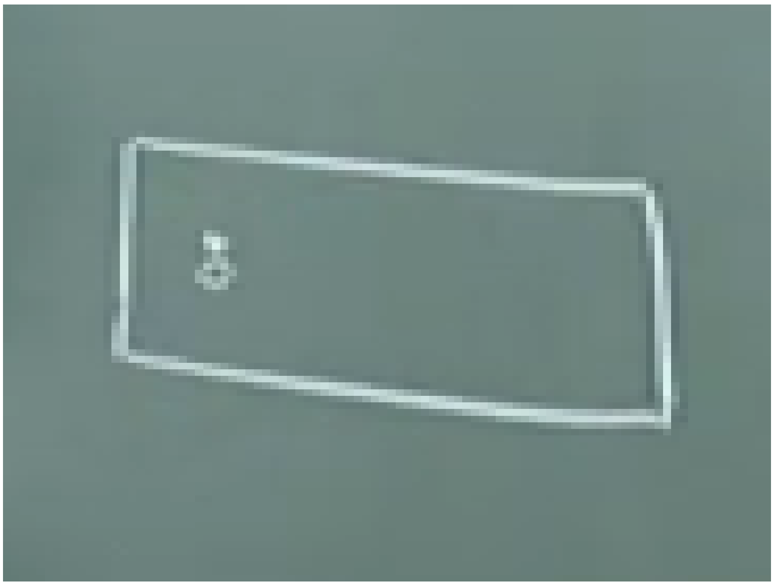

So, the meaning of equilibrium is that if these is the semiconductor sample and suppose that at some location an electron hole pair has got generated. So, we will show a hole by a circle and electron by a solid circle or a dot. Now, if at any instant electron hole pair has got generated here, then at some other location an electron hole pair must be recombined, okay that is the meaning of equilibrium.

Because, for every process, there is an inverse process going on at the same rate. So, it is like you are looking at the sky, at some point a star appears and at the same instant somewhere else a star is disappearing. So, that is the kind of situation, it is like a firework. Now, the next point about equilibrium is shown on the slide, point 2; every process of electron hole pair generation is balanced by its recombination counterpart.

So, you can have 3 processes by which generation or recombination can happen. For example, generation can happen because of energy imparted by photons that is called photo generation, generation can happen because of energy imparted by energetic electrons or hole pair that is called impact generation or impact ionisation and you can have generation because of lattice vibrations that is phonons so that is called phonons assisted generation.

So, as a slide shows equilibrium means that each of these processes of generation namely photo generation, impact generation and phonon assisted generation should be balanced by the corresponding counterpart. So, photo generation is balanced by radiative recombination. So, if generation happens because of energy taken from photons then correspondingly recombination should also happen where in the energy is released as photons, energy and momentum are released as photons.

Now, if recombination is happening because of energy taken from electrons or holes, if generation is happening because of energy taken from electrons or holes, then you should have a corresponding recombination also taking place in the semiconductor where in the energy is released 2 electrons and holes. Finally, if phonons are used to make electron hole pairs, then electron hole pairs will recombine and release phonons.

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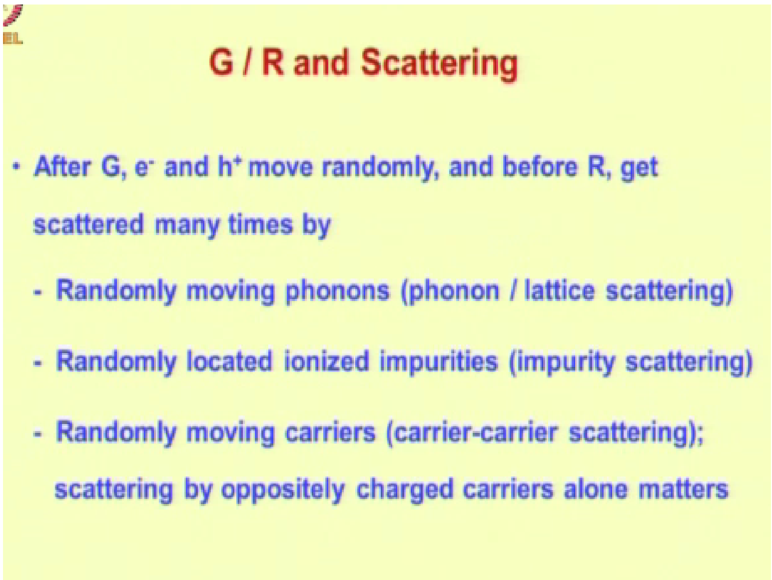

G / R and Scattering

- After G, e^- and h^+ move randomly, and before R, get scattered many times by
  - Randomly moving phonons (phonon / lattice scattering)
  - Randomly located ionized impurities (impurity scattering)
  - Randomly moving carriers (carrier-carrier scattering); scattering by oppositely charged carriers alone matters

So, all these 3 process should exist together with their counter parts, okay. So, this is the meaning of equilibrium, so principle of detailed balance, every process has its inverse. Some more points about generation recombination and scattering. Now, we are adding scattering to generation and recombination. So, after generation electron and hole, they move about randomly and before recombination gets scattered many times.

So like, there is various method of generation, there are various methods of scattering. So, what are the methods of scattering? So, scattering can happen because of randomly moving phonons, these called phonons or lattice scattering. It can happen because of randomly localised ionised impurities that is called impurity scattering and randomly moving carriers, these called carrier-carrier scattering.

So, an electron or a hole after it is generated, it moves about and it can get scattered either by phonons or lattice atoms gets scattered by ionised impurity atoms or by other carriers. Now, among these scattering mechanisms, this scattering by ionised impurities and the scattering by other carriers is called coulomb scattering. Because it is because of forces of attraction or repulsion, the coulomb force between charges.

Now, an important point about the carrier-carrier scattering shown on the slide. The last line, scattering by oppositely charged carriers alone matters, so you know the scattering affects the momentum of the electrons, so electron is moving in some direction. If it gets scattered, it loses momentum in that direction. Now, therefore it is important to understand which type of scattering will affect the current?

So, if an electron gets scattered by another electron though one electron is losing momentum in some direction, the other electron is gaining momentum. So, if you take the electron population as a whole, there is no loss of current. Similarly, for holes, therefore only scattering by oppositely charged carriers affects the current and that is what we must consider in modelling.

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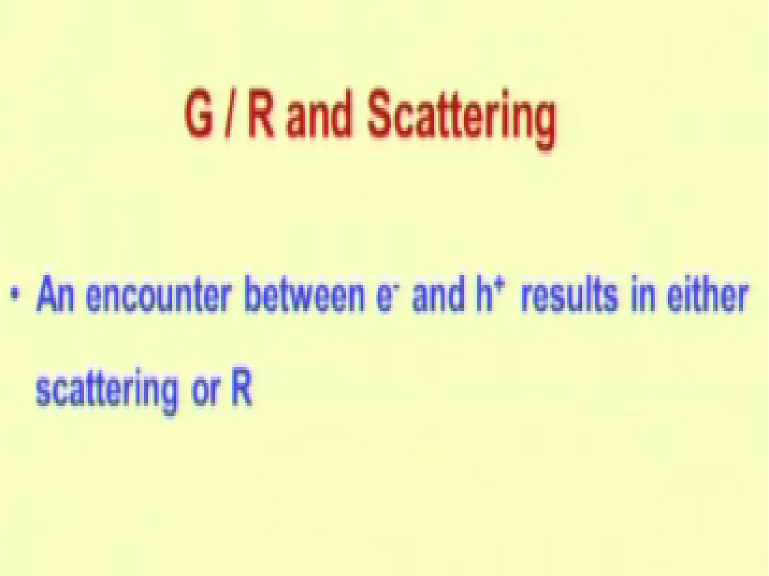

G / R and Scattering

- An encounter between e^- and h^+ results in either scattering or R

The next slide shows another important point and an encounter between an electron and a holes results either in scattering or recombination. So, we must not think that electrons and holes when they come close always recombination will happen even before they recombine with each other, they may get scattered, and their paths may change.

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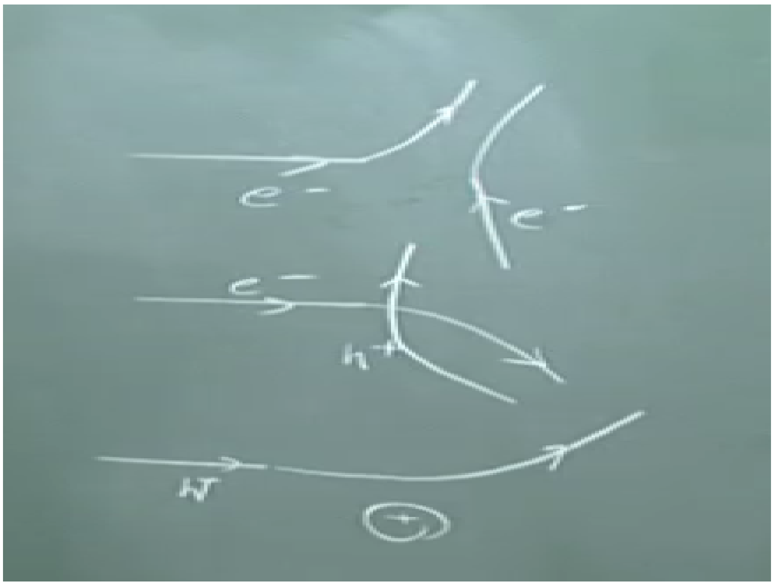

So, for example coulomb scattering because of carriers, suppose an electron is moving like this and an another electron comes in this direction, then what can happen is; this electrons path can change and that electrons path can also change, because they will repel reach other, okay. On the other hand, an electron moving like this, if it encounters a hole, it may get attracted, right.

So, the hole, which is moving like this also may get attract with the electrons, its path may change. Ionised impurity scattering, there is a ionised impurity, let us say it is positively charged, the hole is moving like this as it comes near the impurity its path changes, okay. These are the various mechanisms of scattering. Now what we are saying is an electron and hole, if they bump into each other and get really closed then they may recombine otherwise they will only scatter.

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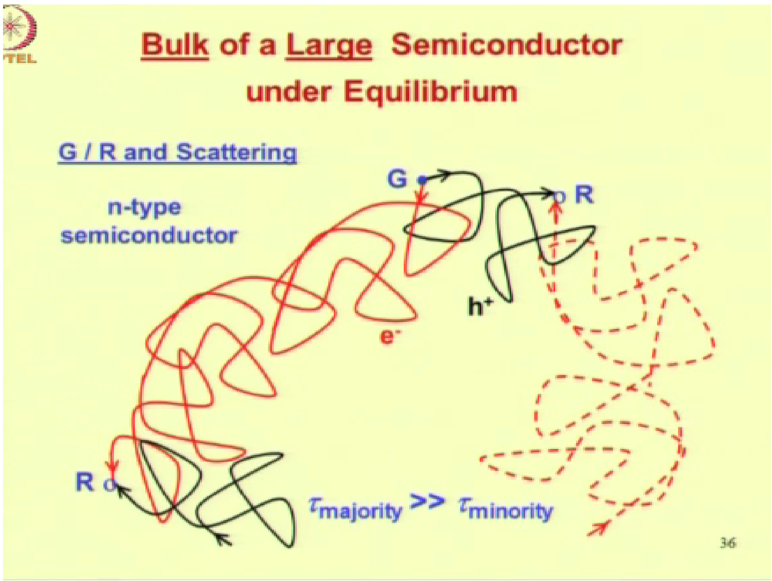

Bulk of a Large Semiconductor under Equilibrium

G / R and Scattering

n-type semiconductor

$\tau_{majority} >> \tau_{minority}$

Now, generation recombination scattering putting all these phenomena together, the picture looks like this, I shown in this slide. So, here we are considering n type semiconductor, the red path; the path in red colour here is that of an electron and the path in black is that of a hole. So, let us take a generation process happening here and electron is created and hole is created.

Now, the electron is moving randomly, it is getting scattered by various mechanisms and ultimately it finds the hole somewhere here to recombine it. Now, the hole which was generated along with this electron at this point, similarly goes about, get scattered many times and it finds in the electron somewhere here. The important point to note here is that between generation and recombination, there are many scattering events.

Further the time between generation and recombination, for a minority carrier is very short as compared to that of a majority carrier. So, you see that in this case for n type semiconductor, the electrons seem to be undergoing many more scattering events and is alive longer than the hole. No, that is represented here by the statement; the lifetime of majority carriers is much more than the life time of minority carriers.

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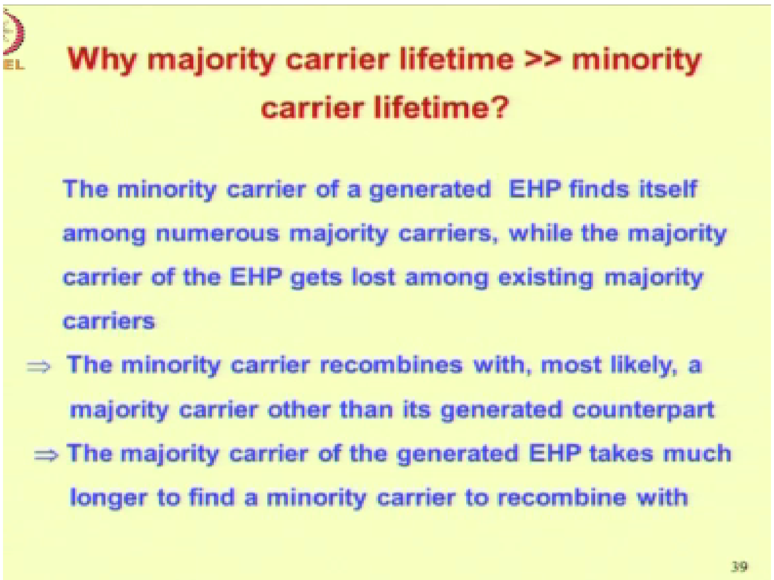

Why majority carrier lifetime >> minority carrier lifetime?

The minority carrier of a generated EHP finds itself among numerous majority carriers, while the majority carrier of the EHP gets lost among existing majority carriers

⇒ The minority carrier recombines with, most likely, a majority carrier other than its generated counterpart

⇒ The majority carrier of the generated EHP takes much longer to find a minority carrier to recombine with

Now, this is an important point that we must note. Now, what is the reason that a lifetime majority carrier is much more than that of minority carriers? Let us put it down in terms of couple of statements. Minority carrier of a generated electron hole pair finds itself among numerous majority carriers while the majority carrier of the electron hole pair gets lost among existing majority carriers.

So, you have too many majority carriers and a very small number of minority carriers. Now, this implies that as a result, the minority carrier recombines with most likely the majority carrier other than its generated counterpart and therefore the majority carrier of the generated electron hole pair takes much longer to find a minority carrier to recombine. So, this is the reason why a majority carrier remains much longer after the generation before it recombines than the minority carrier.

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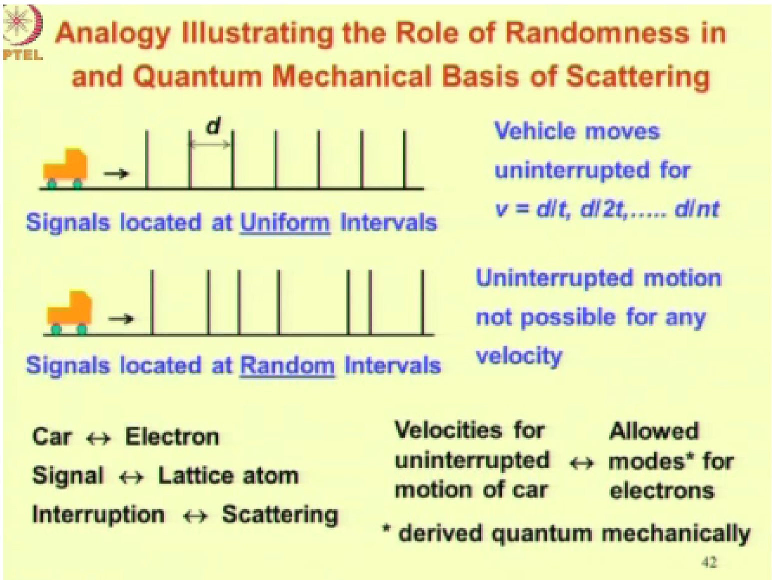

Analogy Illustrating the Role of Randomness in and Quantum Mechanical Basis of Scattering

Signals located at Uniform Intervals

Vehicle moves uninterrupted for $v = d/t,\ d/2t, \ldots\ d/nt$

Signals located at Random Intervals

Uninterrupted motion not possible for any velocity

Car ↔ Electron
Signal ↔ Lattice atom
Interruption ↔ Scattering

Velocities for uninterrupted motion of car	↔	Allowed modes* for electrons

* derived quantum mechanically

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Now, we need to discuss why the mechanism of scattering has to be treated quantum mechanically. So, here is an analogy to illustrate why quantum mechanics is necessary for treating scattering. Consider a car moving on a road which has signals located at regular or uniform intervals, interval between the signals is d. Now, imagine that you are driving the car and you do not want to stop at any of the signals.

Now, can you drive through if you know at what intervals are signal are changing from red to green. The answer is yes, I shown on the slide; the vehicle can move interrupted if you choose your velocity as follows, it is = d/t or d/2t or d/3t or in general d/nt, where d is the distance between the signals and t is the interval in which the signal changes from red to green and now what does it mean?

If I choose my velocity = d/t, it means that when this signal is green, I leave the signal and by the time the next signal goes green, I am right there, so I do not have to stop, I can just drive through and similarly with other signals. Another possibility is that the; I have passed this signal here when the signal has gone green and the next time the signal goes green; the next signal goes green, I am midway, okay.

So, that by the time I reach here, the signal goes green the second time, now this is the lower velocity, so this velocity is d/2t, that is what is indicated here. Now, similarly I could be at one third the distance between the 2 signals, when the next signal is going green and so on. So, this is how I can choose my velocity, okay. A certain velocities, if I choose if the signals are located at regular intervals and if they are changing from red to green also at regular intervals, I can drive through without any interruption.

Now, consider another situation shown in the slide. Now, suppose signals are located at random intervals. Now, it is very easy for you to visualise that even if the signals change from red to green at regular intervals of time, because you do not know the location of the signals, you will have to stop at least some of the signals when you are trying to drive through.

So, you cannot choose any velocity with which you can drive through uninterrupted fashion. Now, this analogy should illustrate to you what happens during scattering of electrons or holes in a semiconductor. So, let us look at the analogous entities here, the car is analogous to the electron, the signal is analogous to the lattice atom, interruption when you are driving the car; stopping the car is analogous to scattering.

Then, velocities for uninterrupted motion of the car are analogous to allowed modes for electrons. So, allowed modes in which the electrons can exist in a crystal. Now, this allowed modes have to be derive quantum mechanics. For example, you know from the courses that you are undergone that electrons can occupy only certain allowed energy levels in a semiconductor in electronic system.

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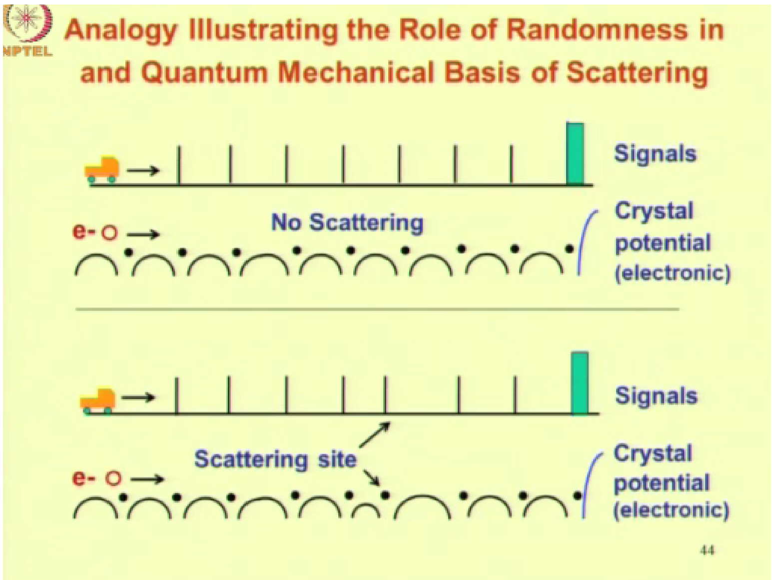

Analogy Illustrating the Role of Randomness in and Quantum Mechanical Basis of Scattering

So, that is what we mean by allowed levels. So, from here we can see that as a next slide show why no scattering of the electron happens if you have a periodic arrangement of crystals atoms. So, you see here the electron if it is allowed into this arrangement we have taken a 1-dimensional arrangement here, it can go through without any scattering just like you can drive the car through without any interruption, if the signals are at regular interval.

On the other hand, suppose even one of the signals is change from its regular position, okay and relocated in a random fashion, then you know that at this point, your car will have to stop. Because, you cannot anticipate, when you will reach this point. Similarly, in a crystal if the regular arrangement of atoms is disturbed at any point in a random manner, then the electron will get scattered at this point.

Now, this reason why we will have to treat the scattering using quantum mechanics because we will have to consider the allowed modes for the electrons and then we will have to see how random variation potential affects these motion of electron in any of the modes. So, supposing you thought about the problem classically then what would your result have been? Now, in classical terms whenever the electron is coming near an atom, it will come into the influence of the atomic potential and therefore it should gets scattered, right.

Whenever an electron comes near any atom, so independent of whether all the atoms are arranged regularly or not, classically speaking an electron coming near any of the atoms gets scattered independent of the arrangement of the other atoms. But we know this is not correct because motion of the electron in a crystal is not affected, if the arrangement of the atoms is regular, if the potential is periodic. Now, this is what quantum mechanics says.

So, that is why we should not look at scattering classically, okay. To further emphasis this point, if you take a silicon crystal at t =0, then it will not scattered, a perfect silicon crystal, okay. There are no impurities, there are only silicon atoms and it is a perfect crystal therefore there all regularly arranged, there are no atomic vibrations, no random vibrations, so in such a case, if you let an electron into the crystal, it will not get scattered.

Whereas classically speaking, you would imagine that there are so many atoms of lattice and if an electron is let into this arrangement, then at least some of the atoms are going to change the direction of motion of the electron but that is not correct. So, this is the reason why you have to treat scattering quantum mechanically and other important point that comes about is scattering happens only if there is random change either in time or in distance of the particular entity, that is scattering.

Now, that is why this previous slide is very important, here we have said that electron or holes they move randomly and gets scattered because of randomly moving phonons, randomly located ionised impurities, randomly moving carriers. So, please understand that its randomness is associated with these entities that are responsible for scattering. Now, we do treat scattering in a classical way after deriving from quantum mechanics that if;

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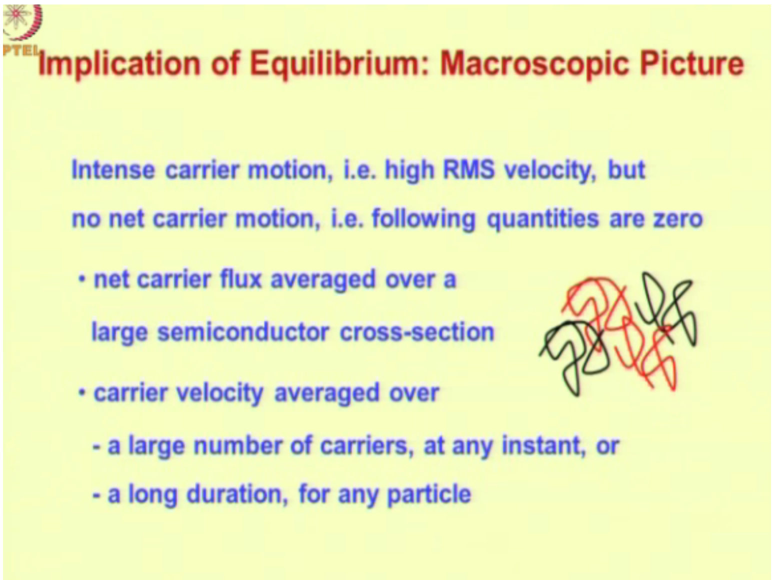

Implication of Equilibrium: Macroscopic Picture

Intense carrier motion, i.e. high RMS velocity, but
no net carrier motion, i.e. following quantities are zero

- net carrier flux averaged over a large semiconductor cross-section
- carrier velocity averaged over
  - a large number of carriers, at any instant, or
  - a long duration, for any particle

For example, ionised impurities located in random fashion then it will scatter, so once you derive the fact that scattering will happen. Then, scattering itself can be treated in the classical manner. Now, let us look at the macroscopic picture, the implication of equilibrium. So, the picture is there is intense carrier motion that is high root mean square velocity but no net carrier motion, okay.

This is the picture under equilibrium the macroscopic picture, the big picture, that there is intense activity at any temperature greater than 0K, you have carriers moving about randomly at high speeds, so that is what is mean by intense activity. But there is no net carrier motion; the word net here is important. In other words, you cannot identify any direction; particular direction in which the carriers are moving, they are moving in all different directions.

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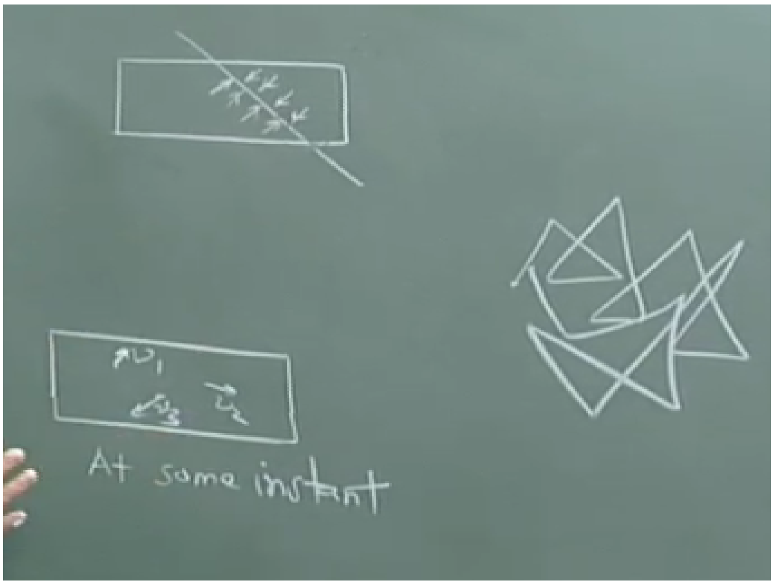

Therefore, let us explain this net carrier motion in terms of more statements. So, following quantities are 0, so net carrier flux average over a large semiconductor cross section. So this means, suppose this is the semiconductor and you take any cross section; large, which means this length is large, I am showing it in 2 dimensions. Then, if I find out how many carriers are moving from left to right in this direction and how many are moving in the other direction.

I will find, rate at with carriers move or cross this plane from this side to that side is the same as the rate at which carriers cross from this side to the other side, okay; that is the meaning; so of no net motion. So, this one interpretation of the statement; no net motion. Another interpretation; the carrier velocity average over a large number of carriers at any instant or a long duration for any particle or any career.

The particle here should be interpreted as carrier is 0, okay so what does it mean? Supposing I take a snap shot of the velocities of carrier at any instant of time, suppose I find this carrier is moving with some velocity v1, another carrier some velocity v2, another carrier some velocity v3 and so on, I take all the carriers, which are present and if I average all these velocities I will get 0, right.

Or if I take any single carrier and follow its path over large number of scattering events, I will find that most likely the carrier will return to its original position; therefore, there is no net displacement. So these n symbol approach in which I look at a large number of carriers at any instant, so n symbol average is 0, or time average, I take one carrier and look at this picture for a long duration of time.

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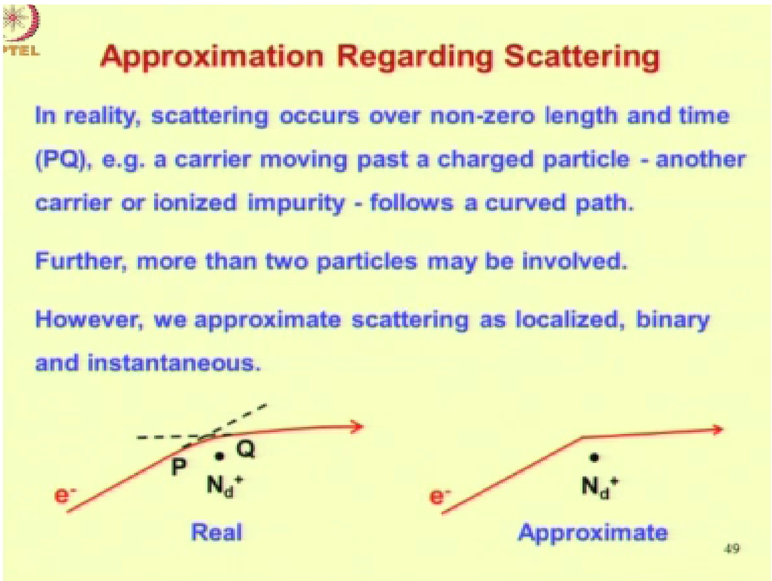

Approximation Regarding Scattering

In reality, scattering occurs over non-zero length and time (PQ), e.g. a carrier moving past a charged particle - another carrier or ionized impurity - follows a curved path.

Further, more than two particles may be involved.

However, we approximate scattering as localized, binary and instantaneous.

So, here we are taking the large number of carriers here we are looking at a single carrier but over a long duration of time. So, then also the average displacement is 0, so that is the meaning of no net motion. Now, let us look at some approximation that we do in our model related to scattering. In reality, scattering occurs over non zero, length and time. So, let me show the diagram here that we tell us, what does P, Q mean?

So, here is the scattering event shown below, so in electron is getting scattered by ionised impurity, which is positively charged say donor impurity. So, this is the coulomb scattering, the path of the electron near the impurity shown here. So, you can see that approximately between the points P and Q the electron is changing its path; direction. So, P, Q is actually this interval. So, in reality scattering occurs over non zero, length and time.

So, P, Q is non-zero, for example a carrier moving past a charged particle another carrier or ionised impurity follows the curved path, so this is the meaning. The path of the carrier during scattering is actually curved. Now, further more than 2 particles may be involved. So, we are looking at only 2 particles but why should only 2 particles be present. Some times, 3 particles may be come together.

And because they are coming together, because of interaction between them all their paths are changes. So, however the approximation we will make is that, scattering is localised binary and instantaneous, so this means binary means that there are only 2 particles involved, localised and instantaneous means the P, Q duration in either distance or time is 0. So, this is approximate picture. We assume that the change in direction of the carrier happens at the point and it happens instantaneously.

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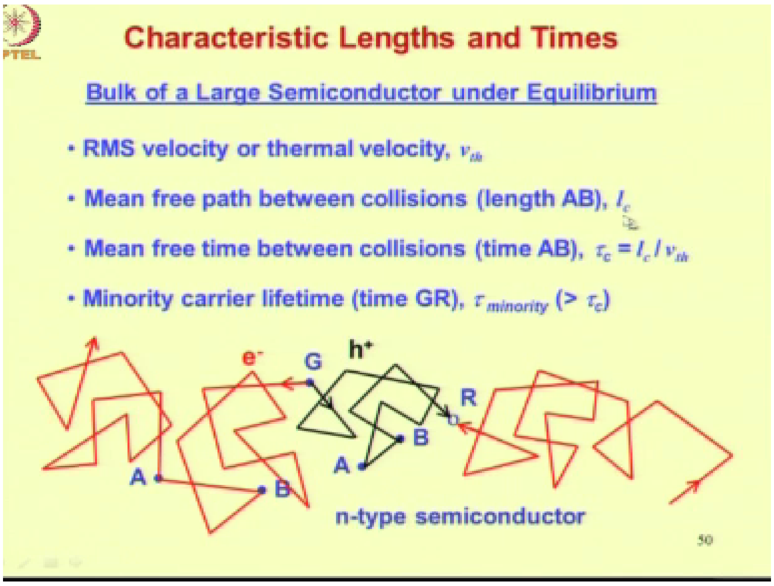

Characteristic Lengths and Times

Bulk of a Large Semiconductor under Equilibrium

- RMS velocity or thermal velocity, v_{th}
- Mean free path between collisions (length AB), l_c
- Mean free time between collisions (time AB), $\tau_c = l_c / v_{th}$
- Minority carrier lifetime (time GR), $\tau_{minority}$ (> τ_c)

n-type semiconductor

So, whenever the electrons come near the any other particle that is scattering, instantaneously the direction gets changed, okay and this happens at a point. Now, let us summarise some of the characteristics lengths and times related to this equilibrium picture. Now, before we talk about the lengths and times, let us talk about the root mean square velocity or thermal velocity.

Now, what is the meaning of the word root mean square? So, at any temperature greater than 0K, we know that the carriers will move out randomly and therefore we can associate a velocity or speed with the carrier. Now, there are different types of averages, for example, in this case, when we talked about the average saying there is no net motion, we talked about simply summing up the velocities taking into account the directions.

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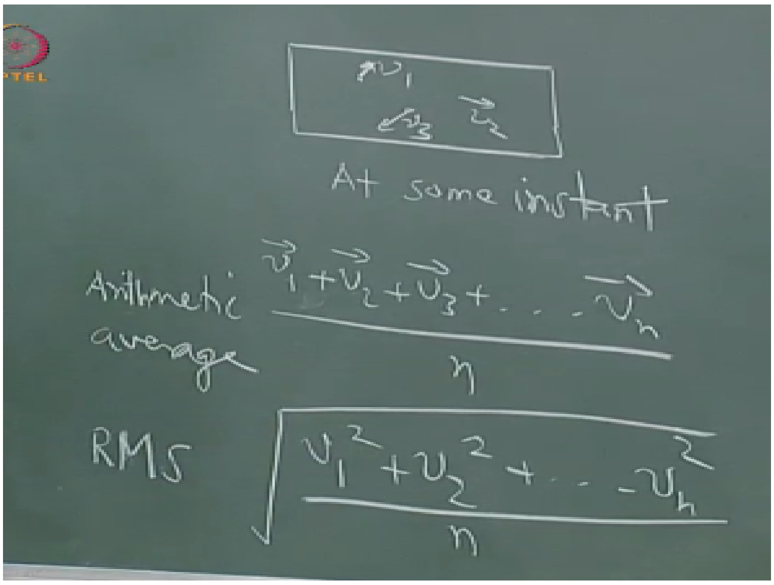

At some instant

Arithmetic average $\frac{\vec{v}_1+\vec{v}_2+\vec{v}_3+\ldots\vec{v}_n}{n}$

RMS $\sqrt{\frac{v_1^2+v_2^2+\ldots v_n^2}{n}}$

Now, as against this kind of an average, which is an arithmetic average, right? So that is v1+v2+v3 and so on divided by so up to vn, the end particles by n, where you taking into account the direction. Let us say, the end particles by n, where you are taking into counter directions, right. Now, these are arithmetic average of the velocities. Now, what is the root mean square average?

The root mean square average as you might probably already know but let me repeat, so root mean square, so you square each velocity. So, squaring of a vector velocity vector means simply taking a dot product, so therefore it is = magnitude v1 square, magnitude v2 square and so on. So, square each of this velocities then take the mean, in other words it will be just take the magnitude v1 square +v2 square so on up to vn square.

Then take the mean, this means I divided it by n and takes the root; r is root, so then I take this. So this is the root mean square value. So, you see this may average to 0, because of the different random directions but clearly this will not be 0, right. This will be a nonzero value, so this actually represents the average speed of the electron or that particular temperature is called root means square velocity.

So, we will represent this velocity which is also called thermal velocity by the symbol v, t, h, I shown on the slide. Now, let us introduce the characteristics lengths and times. The mean free path between collisions that is the length A, B, so what is shown here is the approximated model of the carrier movement under equilibrium, right? So, you see the approximation is that the points at which scattering is occurring, there is a sap change in the path.

So, here the length A, B once you assume that the path changes abruptly then I can always find out the end points of the duration in which no scattering happens. So, I can talk about A, B; the distance and average of this distance for so many carriers taken together is called the mean free path and that is represented by the symbol lc and now supposing we assume the curved path, so the instead of path like this where you know the scattering is happening instantaneously.

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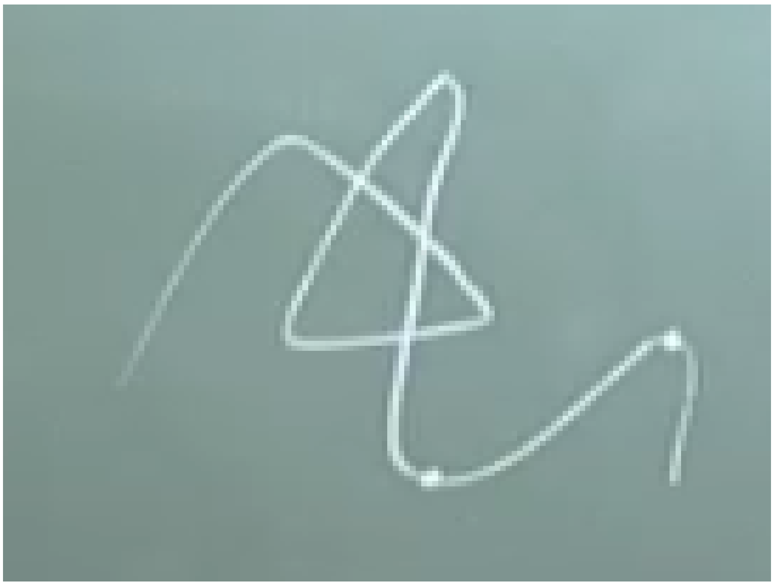

Supposing, we would have assumed a path like this, then since this is a curve, you do not know exactly which point you choose to describe the mean free path but once the power of the sharp, you can really identify the segment. So, in this approximation you can talk about a mean free path that is lc. Next is mean free time between collisions that is the time associated with the path lc.

So, this can be written as in terms of the averages duo c; c stands for collisions, so mean free time between collisions. So, lc here also the c stands for collision is lc / vth. Then another characteristic time is the minority carrier life time that is the time between the events of generation and recombination. So, here in this graph for example the diagram; the red arrow shows the electron and the black the hole.

So, here a generation event has taken place and somewhere here you have recombination. So, the hole is meeting an electron. So, the duration between this G and R for the minority carrier, in this case hole, because we are considering n types symbol, so this is called minority carrier life time. Now, evidently this will be greater than the mean free time between collisions because many collisions take place from generation to recombination.

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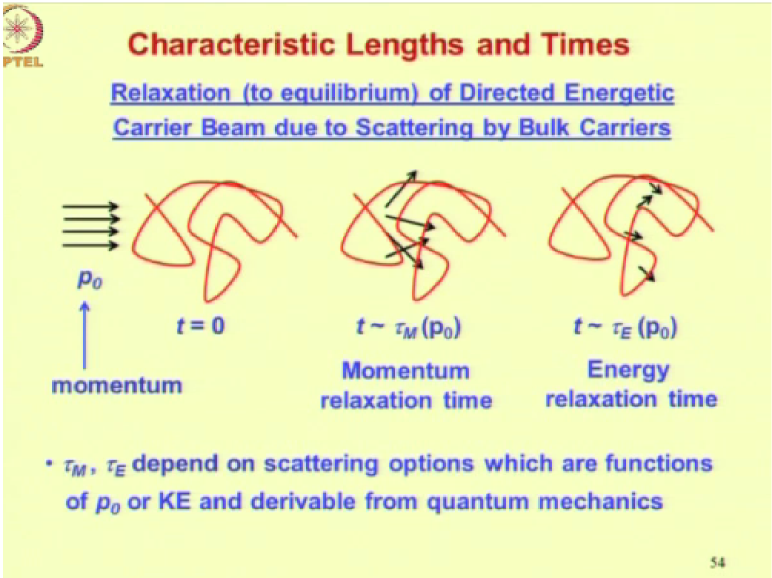

Characteristic Lengths and Times

Relaxation (to equilibrium) of Directed Energetic Carrier Beam due to Scattering by Bulk Carriers

- τ_M, τ_E depend on scattering options which are functions of p_0 or KE and derivable from quantum mechanics

Now, 2 more characteristic lengths and times. These are associated with relaxation to equilibrium of directed energetic carrier beam due to scattering by bulk carriers. So, I shown in the slide, imagine that there is a beam of let us say electrons which have momentum in a particular direction and this beam is let into a population of electrons and holes and may be semiconductor and all other things that are represent like ionised impurity and so on under equilibrium.

Imagine this hypothetical situation. Let us, assume that the beam is really its momentum is really small, so it is a very small beam as compared to the number of carriers and so on, right. So, it is like a very, very small river flowing into a very vast ocean that is the kind of situation you are imagining here, at t =0, the beam is let in. Now, you may get a doubt if you are having electrons all together will they not repel each other?

And how can you have all of them moving exactly in the same direction? Will the beam not divert? Yes, in practice the beam does diverge but here we are making assumptions that such interactions are neglected, so you do have all electrons moving in the same direction. Now, what will happen to this beam? So, you will find that after some collisions the beam would have lost it momentum, so you see the speed of the individual electrons is still the same.

I shown by the length of this arrows, so length of this black arrows is the same as the length of the arrows here to emphasise the fact that the speed is the same, in other words the energy has not really changed but because of scattering event the direction of electrons has been randomised. Now, if you take all electrons in random direction then you sum of their momentums, then you know the net momentum can become close to 0.

Though each of the electron has an energy but the directions are such that their momenta are cancelling each other, now that is what happens here after some collisions and after many more collisions now they will lose their energy as well or their speed as well that is shown by the smaller arrows here. So, the beam of electrons having a momentum first loses its momentum and then loses its energy.

In other words, the energy relaxes much later than the momentum, now this is not at all difficult to visualise why it should be so? So, for example you know that if I hit a ball against a wall, the ball will return in ideal situation with this same velocity with which I hit the wall, okay. So, in other words the balls; momentum has changed its direction of motion has changed but its energy is still the same.

Now, that is the kind of thing that we are talking about here that many scattering events will not change the energy of the particle though definitely it will change the momentum. In scattering, momentum will definitely get changed the path of the electron or hole whatever it is gets changed, okay. Now, this is the reason why the momentum relaxes very quickly but the energy itself is loosed after many more collisions.

So, we can say as follows, some scattering mechanisms are non-isotropic, that is some collision reflect carriers by small angles and so do not affect momentum. In other words, the momentum relaxation time, a time taken for the beam to lose its momentum is greater than the mean free time between collisions, okay. So, now we are now trying to relate the momentum relaxation time and energy relaxation time between among themselves as well as to mean free time between collisions, which we introduced earlier.

So, what we are saying is that just as some collisions do not affect energy, there are some collisions which do not affect momentum to the same extent, okay. Though at the end of this scattering event, the path of the electron will change but in some scattering events the path does not change too much. Therefore, in other words momentum has not been lost to that same extent.

Now this being the case there would be collisions after which the momentum will still remain and therefore the momentum relaxes later than after the momentum relaxation time is more than the mean free time between collisions because there are some collisions which do not affect momentum. Then there many more collisions that the carrier has to undergo before it relaxes energy.

Therefore, the energy relaxation time is more than the momentum relaxation time. Now, that is what is shown here in the slide, many scattering mechanisms are elastic; that is many collisions affect carrier momentum without affecting carrier energy and therefore energy relaxes later than momentum. So, duo E is more than duo M. Finally, duo M and duo E depend on scattering options which are functions of p0, that is the initial momentum of the carrier or kinetic energy and this can be derived from quantum mechanics.

So, the scattering rate has to be derived from quantum mechanics, you recall that we have mention that scattering event has to be treated quantum mechanically and it cannot be done classically. Therefore, the scattering rates have to be derived from quantum mechanics. In other words, the mean free time between collisions, the momentum relaxation time, and the energy relaxation time all these quantities have been derived from quantum mechanics.

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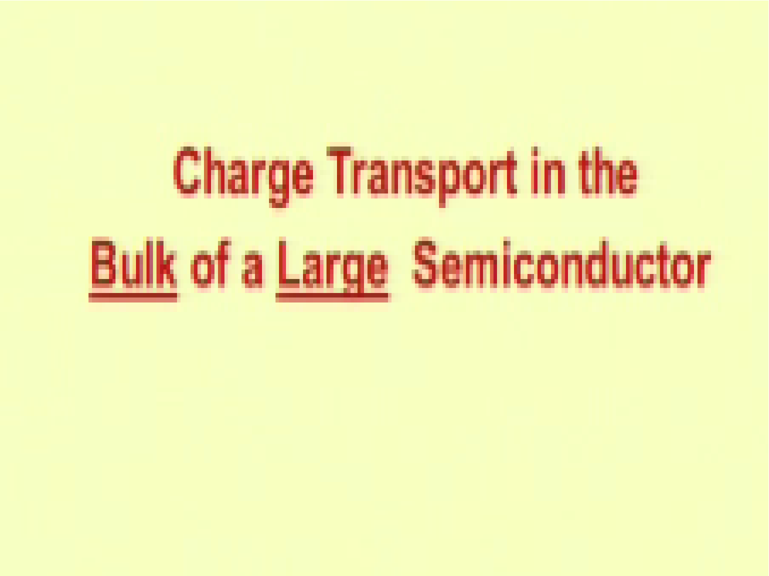

Charge Transport in the
Bulk of a Large Semiconductor

So, that was the picture of the semiconductor under equilibrium. We will now move on to the charge transport in the bulk of a large semiconductor, so what we are discussed under equilibrium is that there are particles moving about randomly, we talked about generation recombination and then we talked about scattering. We captured the picture of the carriers under equilibrium in terms of mean free path, mean free time, minority carrier life time and so on.

We did not talk about; we introduce the minority carrier life time but in the same breadth, we did not talk about majority carrier life time because we will see that it is a minority carrier life time rather than majority carrier life time, which affects various phenomena or which comes into play in various phenomena, because minority carrier lifetime is shorter than majority carrier lifetime.

Now, let us move into charge transport. So, the first question that arises in our mind is; how can you drive the carries in a particular direction. There are already in random thermal motion; please remember this, so whenever we are talking of transport, we must talk about super imposition of a directed motion on this random picture. So, what are the driving forces. Now, let us list the driving forces.

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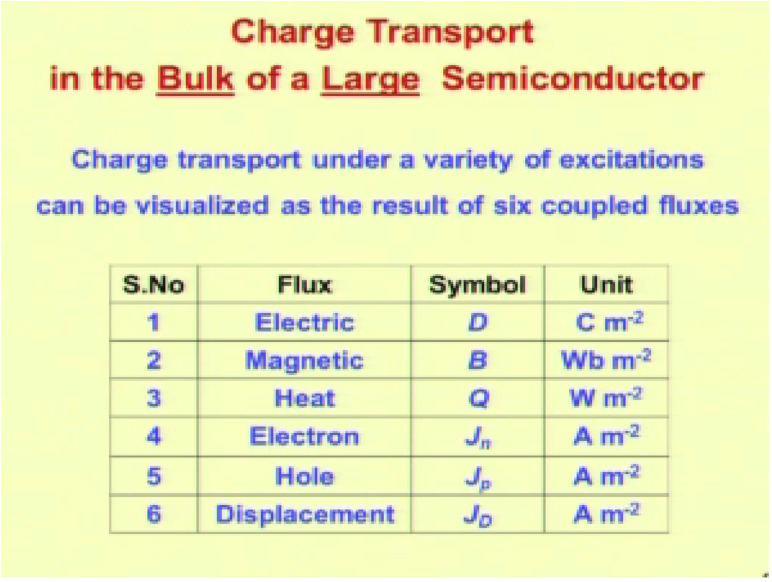

Charge Transport
in the Bulk of a Large Semiconductor

Charge transport under a variety of excitations
can be visualized as the result of six coupled fluxes

S.No	Flux	Symbol	Unit
1	Electric	D	C m^{-2}
2	Magnetic	B	Wb m^{-2}
3	Heat	Q	W m^{-2}
4	Electron	J_n	A m^{-2}
5	Hole	J_p	A m^{-2}
6	Displacement	J_D	A m^{-2}

The charge transport under a variety of excitations can be visualised as a result of 6 coupled fluxes. Now, all the 6 are not necessarily driving fluxes as such, but these are the fluxes, which are present during carrier transport. So, these are the electric flux, the magnetic flux, the heat flux, which can be regard as really the driving forces and the consequences are electron flux, hole flux and the displacement current or the displacement flux.

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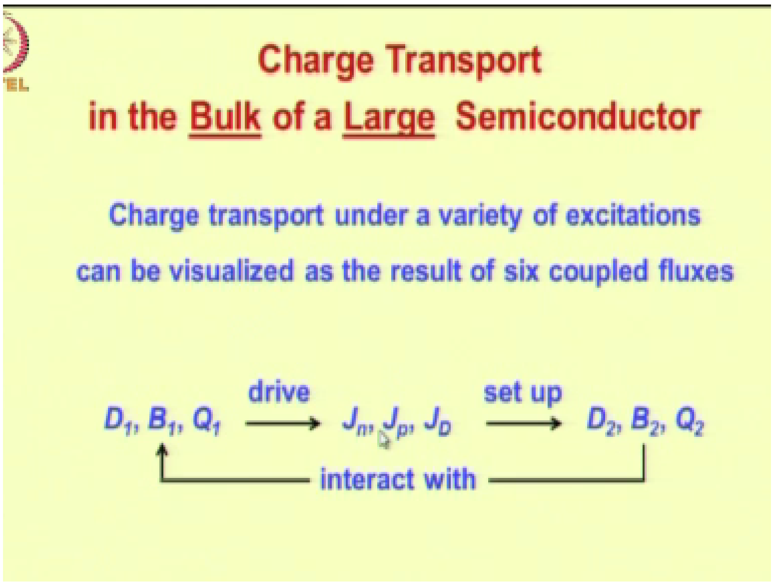

Charge Transport
in the Bulk of a Large Semiconductor

Charge transport under a variety of excitations
can be visualized as the result of six coupled fluxes

$$\begin{tikzcd} D_1, B_1, Q_1 \arrow[r, "\text{drive}"] & J_n, J_p, J_D \arrow[r, "\text{set up}"] & D_2, B_2, Q_2 \arrow[ll, bend left, "\text{interact with}"] \end{tikzcd}$$

Now, notice that the quantities listed here the; D, B, Q, Jn, Jp, JD are all quantities per unit area; per meter square, so that is why they are all called fluxes. Now, let us look at the picture in more detail and set out the interaction between these fluxes, this is done in the next slide. So, I shown here the electric flux, the magnetic flux and the heat flux; they all drive the carriers resulting in Jn, Jp and JD, that is the electron flux, the hole flux and the displacement flux.

Now, what is important to realise the couple nature of these fluxes, now these fluxes themselves set up their own electric flux, magnetic flux and heat flux, okay and this fluxes interact with the driving fluxes that you are applying and that is how the complete picture is built up. Now, how can you have Jn and Jp, JD setting up fluxes, well you know that whenever there is a current, there is a magnetic field around the current, right.

Similarly, whenever there is a displacement current also, there is a magnetic field around it, so that is how you know you are getting the magnetic flux here. Now, similarly when the carriers are moving they can drag the phonons along and that is how you can have a heat flux created by the carriers and similarly you can also have the electric flux, right. Now, therefore the carrier set up the driving forces during their motion.

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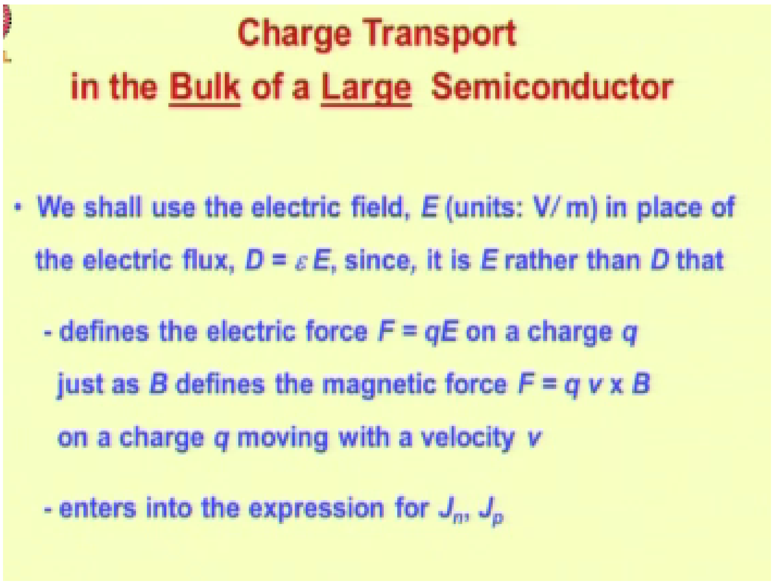

Charge Transport
in the Bulk of a Large Semiconductor

- We shall use the electric field, E (units: V/ m) in place of the electric flux, $D = \varepsilon E$, since, it is E rather than D that
  - defines the electric force $F = qE$ on a charge q just as B defines the magnetic force $F = q\, v \times B$ on a charge q moving with a velocity v
  - enters into the expression for J_n, J_p

So, there is this coupling between the various fluxes; 6 fluxes. Now, how can Q drive Jn or Jp, you know that thermo electric current is there, so that is the mechanism which explains how temperature gradient creates this Q and that Q is responsible for this carriers. Now, we shall use the electric field, which has the units of volt/meter in place of electric flux or displacement that is D, which is given by a epsilon * E.

Since it is E rather than D, that defines the electric force F = qE on a charge q, just has B defines the magnetic force, F = qE cross B on a charge q moving with the velocity v and it is this electric field E that enters into the expression for Jn and Jp. Now, since we wanted to list fluxes which all have analogous units for unit area, we had listed their D in place of E, look at the slide.

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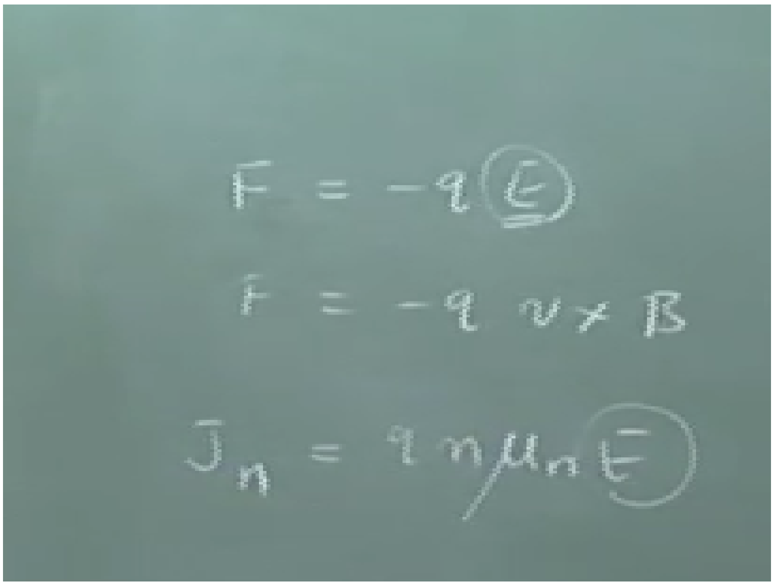

$$F = -q \boxed{E}$$

$$F = -q\, v \times B$$

$$J_n = q\, n \mu_n \boxed{E}$$

So, advantage of using D is that all the quantities involved can be derived as fluxes. On the other hand, the problem with D is that it is not D that is coming into the expression for driving force, so the force on an electron is –q times E, so what is coming there is E. Now, if you want to talk about force due to magnetic field, then expression for that is –q * v cross B, where v and B are vectors.

So, you see that if you are talking about a definition of a force, it is in terms of E and not in terms of D and it is in terms of B not in terms of H, okay. That is why from the point of force e and B seem to be the analogous quantities. Now, similarly if you take expression for Jn, for example the drift expression, which you know from the first level course, so that is qn mu n * E, so here also E enters into the picture and not D.

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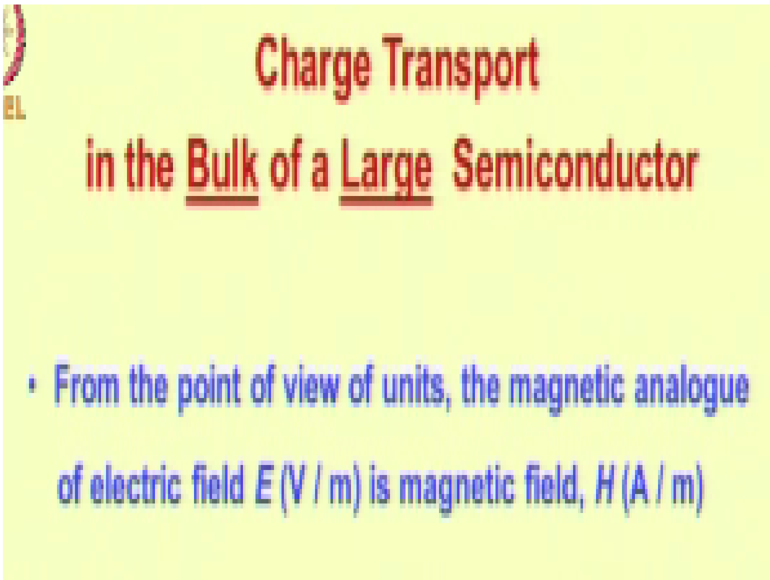

Charge Transport
in the Bulk of a Large Semiconductor

- From the point of view of units, the magnetic analogue of electric field *E* (V / m) is magnetic field, *H* (A / m)

And now for this reasons we are saying that we will use E instead of D. Now, E units are volts/ meter. So, the quantity analogous to E that is in terms of units, the magnetic analogue of E is H, that is ampere/meter, okay. So, this is just for information, so we are going to use E instead of D and other quantities remain D, Q, Jn and Jp and JD okay. Now, as a slide shows since the word flux is replaced by field when using E in place of D.

We refer to the 6 quantities; E, D, Q, Jn, Jp, and JD as flows rather than fluxes, because now we cannot use the word flux, it may be a misconception, it may result in misconception. So, now our picture is modified as E1, B1, Q1 driving Jn, Jp and JD, which in turns set up there E2, B2, Q2 which interact with E1, B1 and Q1. The picture consisting of this 6 fluxes all coupled to each other is rather complex.

So, to proceed further we will have to make some approximations. Now, the series of approximation that we make here will be discussed in the next lecture. Since, we are towards the end of this lecture, let us summarise the important points from this lecture. So, we began this lecture with the discussion of the equilibrium condition, we talked about generation recombination and scattering.

We highlighted the fact that scattering has to be treated quantum mechanically and not classically and scattering happens because of the random nature of lattice vibrations or the random location of impurities or the random movement of electrons and holes, so the randomness is very important for scattering. We also made an approximation related to scattering that though; when the scattering is happening the carrier follows a curved path.

We said that we will assume that the carrier changes its direction abruptly, so in other words the carrier is instantaneous and localised. We also said that we will consider only scattering between 2 entities, so therefore scattering is binary. Then, we introduced some characteristics lengths and times to describe the equilibrium situation, this random motion of carriers. So, we talked about mean free time between collisions, we talked mean free path between collisions.

And then we talked about momentum relaxation time, energy relaxation time, then we also talked about the lifetime of minority and majority carriers. So, we said that the majority carrier lifetime is much more than that of minority carrier. However, the minority carrier lifetime is the one, which plays a role in various effects, and then we made an important observation regarding equilibrium that though there is intense activity at any temperature greater than 0K, there is no net motion in any direction of the carriers.

We interpreted the net motion in several ways. Now, after understanding this equilibrium situation, then we move down to charged transport. So, in charged transport, you disrupt the equilibrium and you super impose the directed motion over the random motion of carriers. Then, we said that the charged transport can be visualised as a result of 6 fluxes namely the electric flux, magnetic flux, the heat flux, the electron flux, the hole flux and the displacement current flux.

So, it is the 6 fluxes, which interact with the each other in carrier transport. Then, we mention that instead of the vector D or the displacement or the electric flux D, we will use the electric field E in all our modelling because the force on charges is given in terms of E and the electric current expression is also given in the terms of E rather than D. Now, in the next lecture we will discuss the serious of approximations that can be used to simply this picture of 6 couple fluxes.