Solid State Devices
Dr. S. Karmalkar
Department of Electronics and Communication Engineering
Indian Institute of Technology, Madras
Lecture - 16
Excess Carriers
(Contd…)

This is the 16th lecture of the series and the 2nd lecture on the Excess Carrier concentration. In the last lecture we saw the various sources of Excess Carriers and then we discussed the concept of injection level and Quasi Fermi-level. We began a discussion of the parameter called the lifetime using an example that is shown here. So this is a transient situation we are going to discuss.

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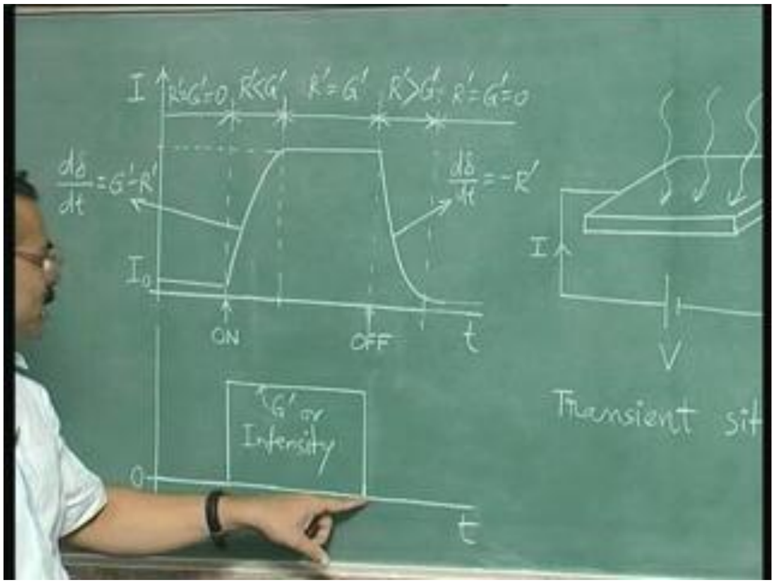

You have a semiconductor on which the light is falling and a voltage is applied so that a current flows. Now we explain the characteristics using this figure. The light intensity is switched on suddenly at some instant then the intensity is maintained constant over a period of time and then it is switched off. The generation rate rises suddenly and it follows the same behavior as the intensity and the resulting current that flows in this circuit however follows this particular shape.

We have explained the various regions and we have said that here the excess generation and recombination rates are 0. R prime and G prime stands for excess generation and recombination rates. They are at 0 and this is the equilibrium state and then there is a state in which although the generation rate has increased suddenly here the recombination rate cannot rise immediately because the carrier concentration rises slowly and then it reaches a steady state when the generation rate is exactly balanced by the recombination rate. And then when you switch the light off the Excess Carrier concentration starts decaying. This is because even though generation rate G dash has become 0 immediately when the light is switched off the recombination rate R dash does not become 0 so it follows a carrier concentration and that is why you have a decay. The decay follows this particular law dalpha by dt is equal to minus R dash.

On the other hand, the rise here follows dalpha by dt is equal to G dash minus R dash i. e the net generation rate. So always the rate of increase of Excess Carrier concentration depends on the net generation rate. So here also this is a net generation rate but since the excess generation rate is 0 it is only the recombination rate that is causing the decay. Now let us proceed further from here to discuss the concept of lifetime. Let us look at this particular situation the decay. It has been observed that if the intensity of light that is falling here is small enough so that the injection level in the sample is low then this recombination rate R dash can be written as alpha by tau where tau is a time constant, alpha is Excess Carrier concentration meaning the excess recombination rate is proportional to the Excess Carrier concentration.

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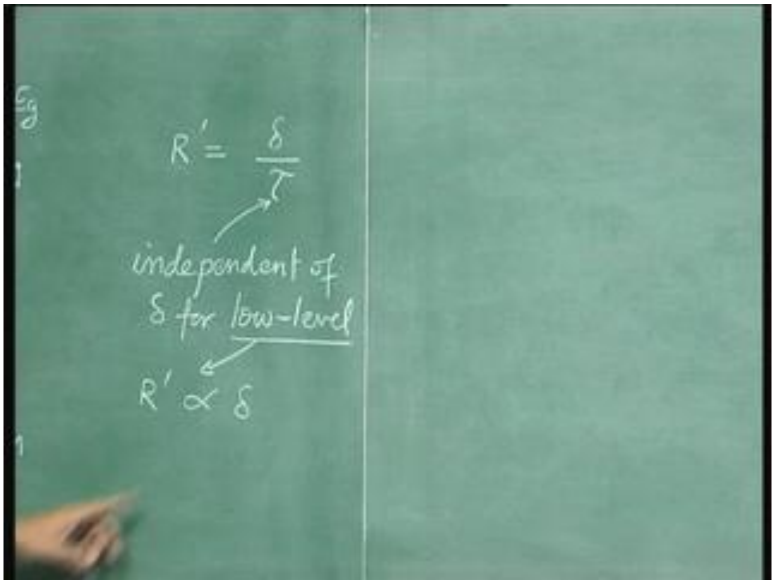

Under low injection level this time constant here will be independent of this Excess Carrier concentration so tau is independent of alpha for low level. In other words R dash is proportional to alpha under low level conditions. So under low level conditions the analysis of device is simple and we are going to concentrate on low injection level. We can therefore write this equation dalpha by dt is equal to - R prime as $\frac{d\delta}{dt} = \frac{\delta}{\tau}$ this particular time constant tau so that is the rate of decay.

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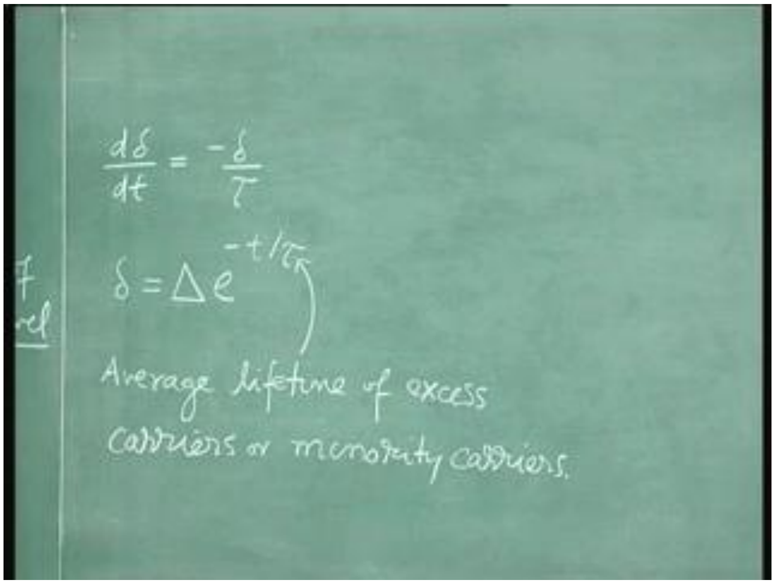

$$\frac{d\delta}{dt} = -\frac{\delta}{\tau}$$

$$\delta = \Delta e^{-t/\tau}$$

Average lifetime of excess carriers or minority carriers.

Please note that we have emphasized this in the last class. We are assuming that the Excess Carrier concentration is uniform throughout the volume and this rise of the concentration or the fall of the concentration is not because of any net input or net output of holes from any of the regions which means there is no flow of carriers. You have neglected any carrier flow carrier flow is assumed to be 0 so this rise and this fall is only due to either generation or recombination. Under such situation when you have only excess recombination present this is the law.

Let us try to interpret the time constant tau. The solution of this equation clearly is alpha is equal to Δe – t by tau where alpha is nothing but its value at t is equal to 0. Now once we know that this is a solution we can interpret this time constant T as the average lifetime of the Excess Carriers. It also called the average lifetime of the minority carriers. We will show why it is to be called the average lifetime. First let us write down the two names for these time constants? So it is average lifetime of Excess Carriers or minority carriers i.e. theta. Now is to be noted here that tau cannot be called the lifetime of majority carriers which we will see later. First let us explain why it should be called average lifetime of excess carriers. Now you see from here that this is the rate of decay. Since the decay of carrier concentration is exponential the average lifetime of the carriers in a exponentially decaying population. What is average lifetime of the carriers in the exponentially decaying population? Now this can be obtained using the following formula.

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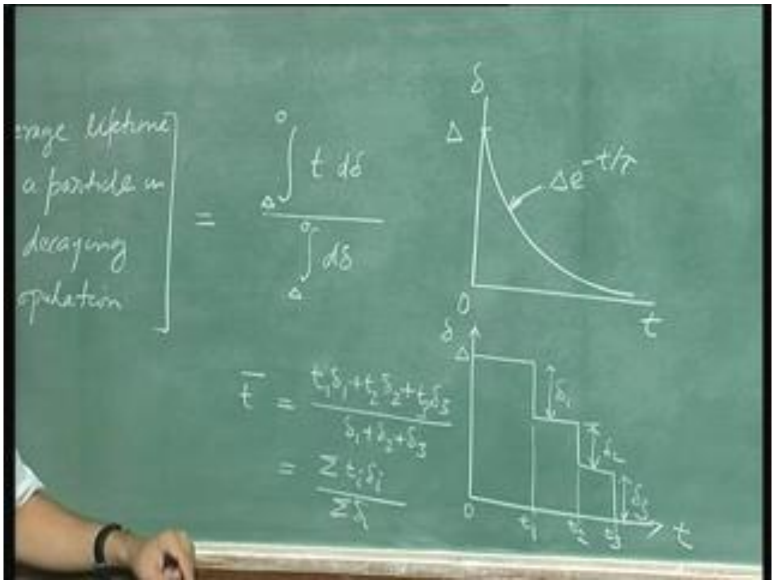

So average lifetime of a particle in a decaying population is given by $\frac{\int_\Delta^0 t\, d\delta}{\int_\Delta^0 d\delta}$ this formula is your carrier population that is decaying. This is alpha e to the power minus t t by T and this is the time axis. If for this particular decay you want to know the average lifetime of carriers then it is given by this formula. So alpha is the value of the Excess Carrier concentration at t is equal to 0 and then this is a t is equal to infinity because Excess Carrier. Concentration is falling to 0, this is Excess Carrier axis. Any such decay implies that all the carriers in the population do not have the same lifetime because if all the carriers were to have the same lifetime then the carrier concentration would stay constant for that amount of time equal to the lifetime and then it would suddenly drop to 0 because all the carriers will get killed suddenly. But the very fact that it is gradually decaying means all the carriers do not have the same lifetime. Therefore we have to talk of an average lifetime of the carrier in this population.

Now, how do you interpret this formula? How do you get this formula as the average? This can be understood using this diagram where I am going to show an approximation of this decay as something like these steps so this is alpha versus t and this is alpha$_1$, this is alpha$_2$ and this is alpha$_3$. This is t_1, this is t_2 and this is t_3, this t is equal to 0 and this initial value is alpha. So a figure like this implies that alpha$_1$ Excess Carriers have a lifetime of t_1. So after t_1 duration alpha$_1$ carriers have got killed and that is why Excess Carrier concentration has fallen by this alpha$_1$ then after another time t_2, alpha$_2$ carriers have been killed therefore the Excess Carrier population has fallen down by further alpha$_2$ and so on. The remaining alpha$_3$ carriers have decayed at the end of t_3 which is the lifetime of these alpha$_3$ carriers. So t_1 is a lifetime of alpha$_1$ carriers, t_2 is the lifetime of alpha$_2$ carriers and t_3 is the lifetime of alpha$_3$ carriers in this population of alpha carriers. Then what is average time for which a carrier stays in this population or the average lifetime of carriers? It can be written as t_1 alpha$_1$ plus t_2 alpha$_2$ plus t_3 alpha$_3$ by alpha$_1$ plus alpha$_2$ plus alpha$_3$ so that is the weighted average of the lifetime of individual populations in this decay. This is the average lifetime the t average. It is evident that this is nothing but you can write it generally as$\frac{\Sigma ti\delta i}{\Sigma\delta}$.

Now, if we go on reducing the size of these steps and we adjust this particular step like distribution you will get this exponential distribution. Therefore in such a limit when each of these alphas becomes very small then alpha i can be replaced by dalpha and the t_i is replaced by t. The summation sign is replaced by the integration sign, this summation is again replaced by integration which gives you equation for the average lifetime of carriers in this decaying population. Now, this is nothing but integral tdalpha by alpha with a minus sign and since the negative sign is there I will change the limits and make it 0 to alpha. So the denominator is minus alpha which I have put as alpha and I have changed the limits of the numerator so this is the equation.

Now, I will leave it as an exercise for you to show that when you replace td alpha by the expression obtained from here t into d(alpha e to the power minus t) by T integral by alpha from 0 to alpha. Since this is the function of t what you should do is finally you will get this as a function of t and when you do the integration you will have to change these limits as alpha is equal to 0. This is infinity t is equal to infinity and alpha is equal to alpha t is 0 so this is the equation. And one can show that this is equal to tau so this is left to you as an exercise to show. Therefore the average lifetime of carriers in an exponentially decaying population is the same as the time constant of the exponential and that is this T. That is why we interpret this tau as average lifetime of Excess Carriers.

Why do we call it as average lifetime of minority carriers which is another name to this? Now, this is because we know that the minority carrier population is approximately equal to Excess Carrier population because minority carrier population is so small that even if the injection level is low right the carrier concentration of Excess Carriers would almost be the same as carrier concentration of minority carriers. Minority carrier concentration is always disturbed and is almost equal to the Excess Carrier concentration and that is why we can also call it as lifetime of minority carriers.

However, we cannot call it as lifetime of majority carriers because majority carrier concentration is not exactly equal to the Excess Carrier concentration. In fact under low injection level the majority carrier concentration is not disturbed at all. The Excess Carrier concentration is much less than the majority carrier concentration so you cannot call T as the lifetime of majority carriers, this is important to understand. Also, note that the concept of lifetime as discussed here is strictly valid only for low injection level because as we said here this tau is independent of alpha only under low injection level and only then you will get this exponential decay and only then you can show this tau as the average life time of carriers in the decay. Although the concept of lifetime is valid only for low injection level in some modified form it is used under all conditions.

Now the next step would be to theoretically show how you get an expression of this form for the phenomenon of excess recombination. Right now we have said that this is observed and from the observation we have introduced the concept of lifetime. Now we need to get expression for this lifetime and show that indeed you will have in this form of excess recombination if you start from theoretical principles. The first step in this is to consider the various mechanisms of generation and recombination in different semiconductors.

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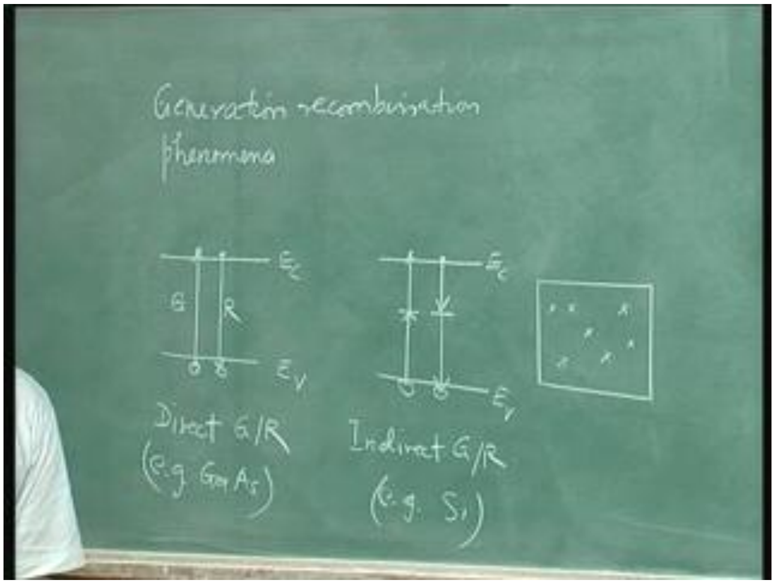

Generation recombination phenomena: Now, we may tend to think that whenever an electron meets a hole the recombination occurs. Strictly speaking this is true only in semiconductors such as gallium arsenide. Wherever a electron meets a hole recombination occurs or wherever in the semiconductor sample a electron meets a hole recombination occurs.

On the other hand, it is found that in certain semiconductors like silicon it is necessary that when the electron is meeting a hole it is necessary that there be an impurity or some other agency present for the recombination to occur. In semiconductors like silicon the recombination will not take place in all regions of the semiconductor where an electron meets a hole. It is only near certain sides within the semiconductor if the electrons and holes meet recombination can occur. Therefore we need to understand this particular aspect in detail.

Let us look at the generation recombination from the energy band point of view which is the process in which the electron recombines with a hole without the aid of any other agency. So whenever electron and hole meet they are recombining and this is shown here on the energy band diagram. This is recombination and the reverse of this is generation. Now this particular process of generation recombination is called direct generation or recombination because wherever the electron and hole meet each other they can recombine so the electron is jumping directly into a hole on the energy band diagram.

As against this the recombination in the semiconductors such as silicon, this direct recombination takes place in semiconductor such as gallium arsenide, so in silicon the process occurs as something like this. The recombination occurs when an electron jumps to the side called the impurity side or an intermediate level between the conduction and valance bands and then it jumps down into the valance band. So the generation similarly occurs by electron jumping from valance band to this sight the impurity level or defect level and then it jumps up which is called indirect recombination. This particular process is indirect because the recombination occurs via an impurity level or defect level within the energy gap. Physically this means that if this is a semiconductor block there will be some locations in this semiconductor block where there will be defects or impurities and these defects or impurities will have an energy level between the E_c and E_v levels somewhere in the energy gap.

Why at these particular impurity sites the recombination is occurring? If the electron and hole meet at this site the recombination will take place. There are some qualifications for the impurity or defects sites to act as recombination centers. Now what are those? An important qualification is that the energy level corresponding to this particular site which must aid recombination should be somewhere near the middle of the energy gap, You can see here that this level is somewhere near the middle, it is not necessary that it exactly should be in the middle but somewhere near the middle. Why? This can be understood with the help of simple analogy.

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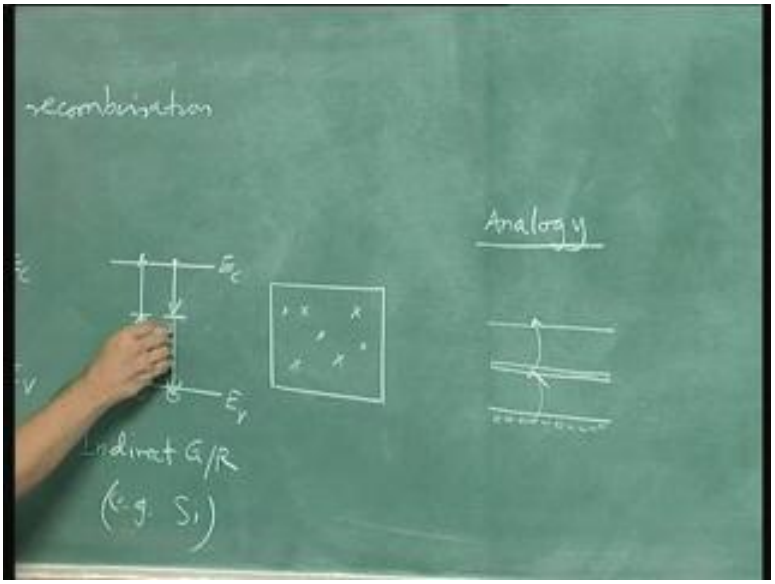

Imagine that you have a narrow channel across which people want to jump so you have a large number of people lined up here who want to jump across the channel. The channel is narrow but it is not so narrow that all the people can jump very easily. Now, you find out how many people are able to jump this channel. Now you want to create a situation where all the people would be able to jump. The best way you can do it is to introduce a step in between. So imagine that you have introduced a step in between here in the channel so that people can first jump on to this step and then they can jump to the other bank of the channel. Where would you locate this step so that the situation is easiest for all the people? Now it is evident that if you now locate this step very close to this end then the effect of the step is not important, the step is not making your job easy at all because you have to jump this long distance.

On the other hand, if your step is close to this end then also it is of no use because you have to jump, the first jump is easy but the second jump is difficult so both the jumps should be equally easy and only then this situation is favorable. This means your step should be in the middle or at least somewhere near the middle then all these people would be able to jump across easily. In a similar manner, the energy level corresponding to the particular impurity site which wants to act as recombination centers should be somewhere in the middle. In other words this should be what is called deep impurities. So these are deep impurities. There can be defects also so let me not call them as impurities alone but we will call them sites having deep levels. So the energy level corresponding to these sites is deep so only at such sites the recombination can occur. This is called as the indirect recombination.

It is evident that in such semiconductors as silicon where the recombination can only occur at deep impurity sites the rate of recombination is much less than in semiconductors like gallium arsenide where the recombination can occur anywhere where the electrons and holes meet. This has been found by experiment that the lifetime of Excess Carriers in gallium arsenide is very low meaning their recombination rate is very high as compared to silicon where the recombination rate is much lower. We need to explain why this kind of recombination is not possible in silicon?

What is the difficulty in having valid recombination in silicon? To explain this particular aspect we need to consider the momentum of electrons in the conduction band and in the valence band. This particular diagram here shows the change in energy of the electron which is taking part in recombination. We also need to consider the change in momentum because as we have said earlier generation recombination phenomena can be treated as collisions among particles. So recombination can be treated as a collision between electron and hole where both the particles are annulated and the energy as well as the momentum therefore should be dissipated so it should be given away to some other particle. What is that particle and how much is the change in momentum? The change in momentum will decide as to which particle the energy and momentum can be given away. Next let us discuss the momentum considerations in transition of electrons from conduction to valence band.

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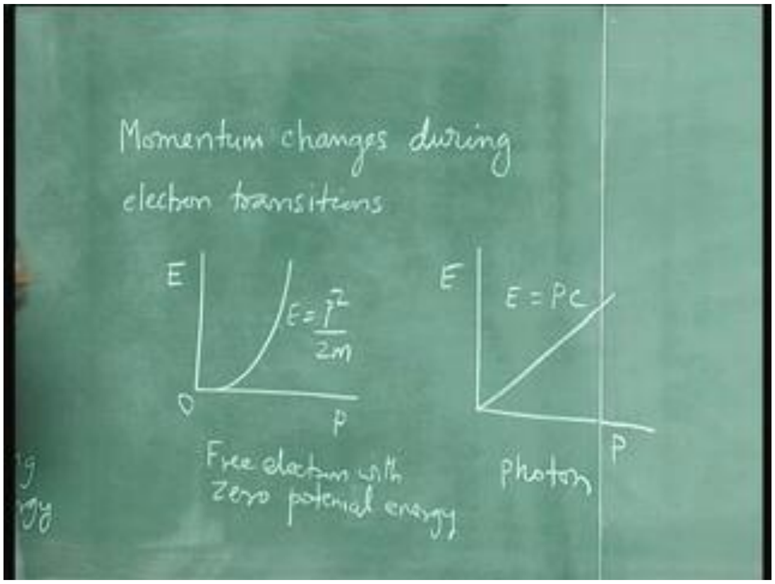

Momentum changes during electron transitions: For this purpose we need to draw what is called an energy momentum diagram. In this particular energy band diagram the momentum considerations are not shown so we need to plot energy on the vertical axis and momentum on the other axis and then we can understand the changes in momenta during transitions very easily.

How do you get the energy momentum diagram of electrons in the conduction and valence band?
To understand this let us start with the energy momentum diagram of free electron. So it is free electron with zero potential energy and for this the energy momentum diagram will be something like this. This is energy, this is momentum, p is momentum so this equation is $E = \frac{p^2}{2m}$ it is a free electron which means electron in vacuum so it has only kinetic energy because potential energy is 0 then you know that the kinetic energy can be written as p square by 2m so this is the shape of energy momentum diagram for a free electron. Let us see the diagram for a photon. For a photon it is just a straight line because the equation is e is equal to p, the momentum multiplied by c is the velocity of the photon. Now, in a similar manner one can draw the energy momentum diagram of an electron in a periodic crystal potential. Please understand that when we are talking of electron in a crystal it is electron in a periodic potential.

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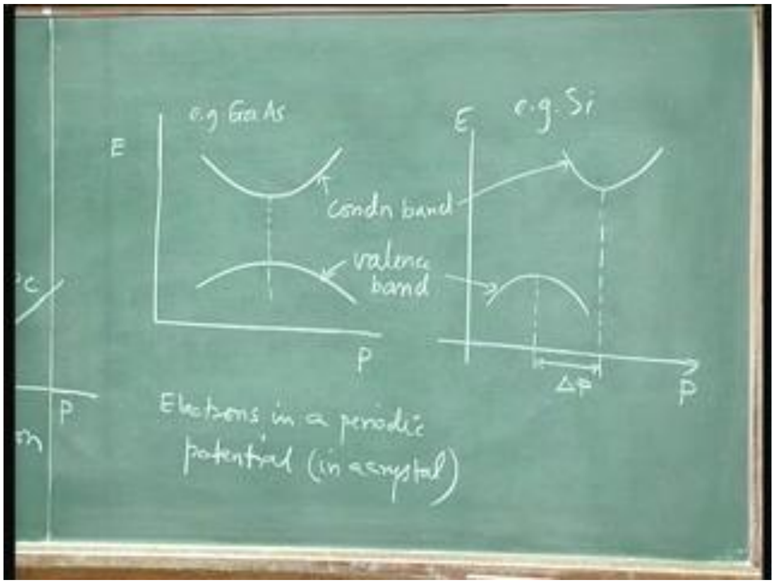

It turns out that the diagram looks something like this: So this is electrons in periodic crystal potential or periodic potential in a crystal. How does this look like? It is somewhat more complicated. Let us draw it first and then give an explanation, so this is E. For an electron at conduction band edge in some semiconductors the energy versus momentum diagram is this and for the valence band this is conduction band and this is valence band. In some semiconductors the diagram is something like this. Therefore, the minimum of this particular energy momentum line is aligned to the maximum of energy momentum line corresponding to valence band as shown here. This is true for some semiconductors such as gallium arsenide whereas in some other semiconductors such as silicon the picture is like this for example silicon.

Here what you find is a minimum of this energy momentum relation for the conduction band and the maximum energy relation of the valence band there is a difference alpha p, this is the picture in silicon. Now, how do you get these kinds of diagram in semiconductors? You know that electron in the crystal can be treated as either as a particle or as a wave. When electron is treated as a wave then for any traveling wave there is what is called a dispersion relation i.e. frequency versus lambda relation.

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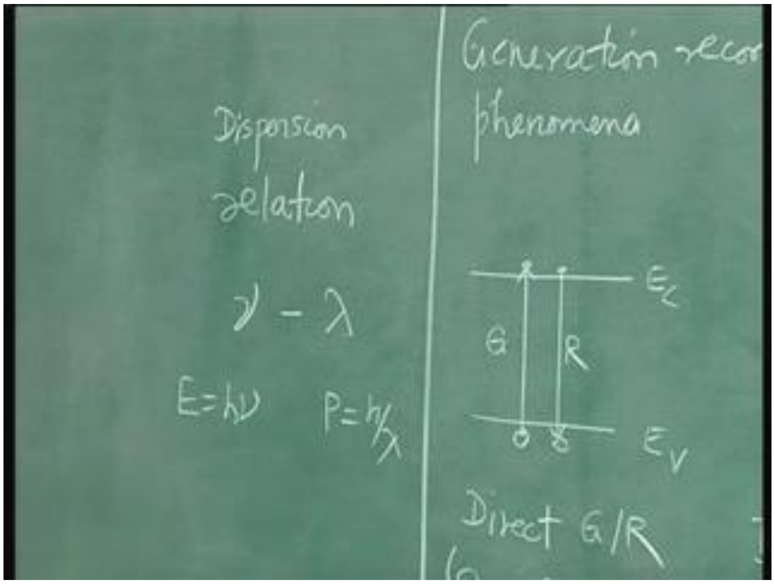

For any traveling wave you will have a relation. For any traveling wave there is a dispersion relation that gives you the relation between frequency of a wave and the wave length of lambda. Now by wave particle duality you know that the frequency can be related to the energy because E is equal to hmu and the wavelength lambda can be related to the momentum because p is equal to h by lambda. So this mu lambda relationship can be converted into energy momentum relationship and that is how you obtain this energy momentum relationship for an electron in a crystal.

Please note that here p is referred to as crystal momentum and this is not the same as the momentum of free electron. So this is the picture in a crystal, it is obtained from the wave particle duality relationship using the dispersion relation. One must be careful in interpreting the momentum. For example, here the momentum corresponding to the energy is the same even though the energy is different in the conduction and valence bands. How can this happen? One may get a doubt because if the energy is changing the momentum should also change. But this is where you must know that we are taking of crystal momentum and this is some kind of an imaginary concept where you are talking of momentum of a electron as derived from wave particle duality. So once you understand this then you will not confuse this momentum with the momentum that is written here for a free electron.

Like hole is an imaginary concept the crystal momentum is a concept that is introduced to simplify the situation of a wave particle duality. Electron is actually a wave so you are looking at the wave as a particle converting the wave nature into particle nature so that you treat the collision phenomenon in a classical manner. This means that in semiconductors such as these when an electron undergoes the transition from conduction to valence band it will not have any change in momentum.

On the other hand, in semiconductors such as silicon it clearly shows that when electron makes the transition from the conduction to valence band during recombination there will be a change in momentum that is lambda p and this change in momentum has to be dissipated. So this is the momentum lambda p that will have to be dissipated in a recombination process. Here the recombination transition is shown like this. The generation will be exactly the reverse of this. You just reverse the arrow here and the arrow here you get the generation process.

Now in terms of this picture one can explain why direct recombination is difficult in silicon. In silicon if an electron has to recombine with a hole the momentum has to be dissipated and if you look at the momenta of different particles such as photon, the phonon and other electrons and holes which are present then it will be clear that this momentum cannot be given to the photon but it can only be given to a phonon or a particle. And then one makes the rigorous calculation of what is the possibility of the momentum being given to photon or a phonon. And then one finds that unless a third particle is involved this process the probability is very low.

We are not going to discuss this issue rigorously because you need to know much more amount of Physics to understand this but you will accept this as a statement of fact, that to dissipate this momentum you need and an external agency or a third particle. It turns out that this deep impurity here or these kinds of sites where it can be a defect or an impurity having a deep level are very useful in enabling the electron to dissipate its momentum in silicon like semiconductors where these are called indirect semiconductors.

So, this is the example of energy momentum relationship in a direct semiconductor and this is an example of energy momentum relationship in an indirect semiconductor. Another thing that can be seen here is that in direct semiconductors there is no change in momentum and therefore the energy that an electron has to release during recombination can be given to a photon .The momentum change or the amount of momentum that a photon has for any given energy is very small compared to that of a phonon or an electron.

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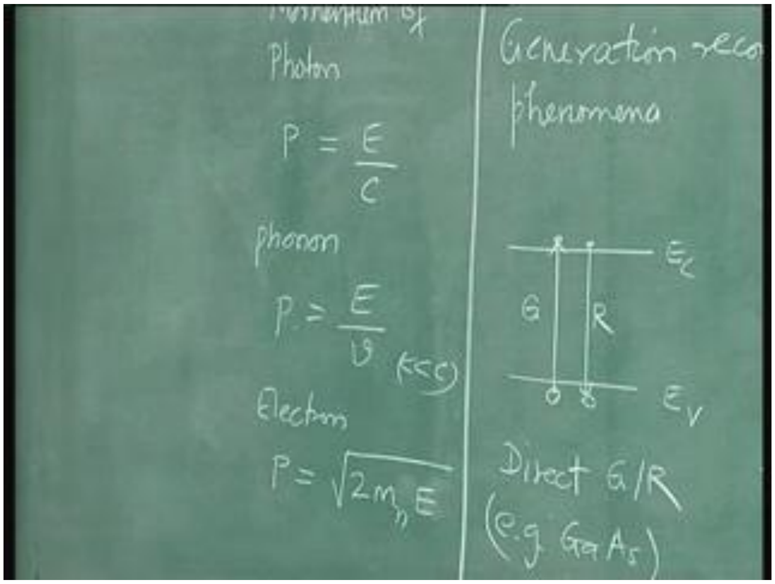

The momentum of various particles: Photon where p is equal to h by lambda i.e. we want to write the momentum of photon, phonon and an electron for the same energy. For a photon the momentum P is equal to E by C the velocity, for a phonon the momentum P is equal to E by V(less than cc). So that is how you see that a phonon has a large momentum as compared to photon, this c is large so momentum is small. Whereas the momentum of a particle such as electron for example in a crystal will be given by P is equal to $\sqrt{2Mn(\text{ KE})}$ where M is the effective mass because you have to use p square by 2m which is the kinetic energy. We will assume that E is kinetic energy so let us retain this symbol e here. So one can estimate for any given energy the momentum of a photon, the momentum of a phonon and the momentum of an electron and that is how one arrives at the conclusion that a negligible change in momentum is involved here, the momentum can be given to a photon and that is why the radiative recombination is possible in gallium arsenide.

Therefore direct recombination is possible and the direct recombination is radiative in semiconductor such as gallium arsenide. Using these same relationships one finds that the momentum of a phonon and momentum of electron is fairly large for any given energy and therefore one arrives at the conclusion that in indirect semiconductor such as silicon or the indirect recombination the momentum can only be dissipated to phonon or an electron and the process of dissipation of a momentum to a phonon is aided considerably if a third particle is present near which the recombination occurs. This third particle or external agencies are the sites which have deep levels.

Incidentally here this is the E_c and this is E_v. And similarly here this is E_c and this E_v where this is an energy gap so this is also an energy gap here. Based on this diagram one can explain how gallium arsenide and other compound semiconductors which have direct band gap. This is an example of direct band gap semiconductor where the momentum change is 0 for the transition. So these direct band gap semiconductors are suitable for optoelectronic devices where you want to convert electrical energy into light. So light can be emitted when the Excess Carriers are recombined.

On the other hand, in silicon light cannot be emitted because of this alpha p associated with the recombination in silicon. Therefore the recombination in silicon non radioactive and you cannot use silicon for emitting light. You may detect light, create Excess Carriers by illumination but you cannot emit light through recombination of Excess Carriers in silicon. So, in indirect band gap semiconductors light cannot be emitted and therefore it cannot be used for application such as LEDs Light Emitting Diodes and things like that. Now let us discuss the expressions for these recombination mechanisms and show that under low level conditions the excess recombination rate will be proportional to Excess Carrier concentration.

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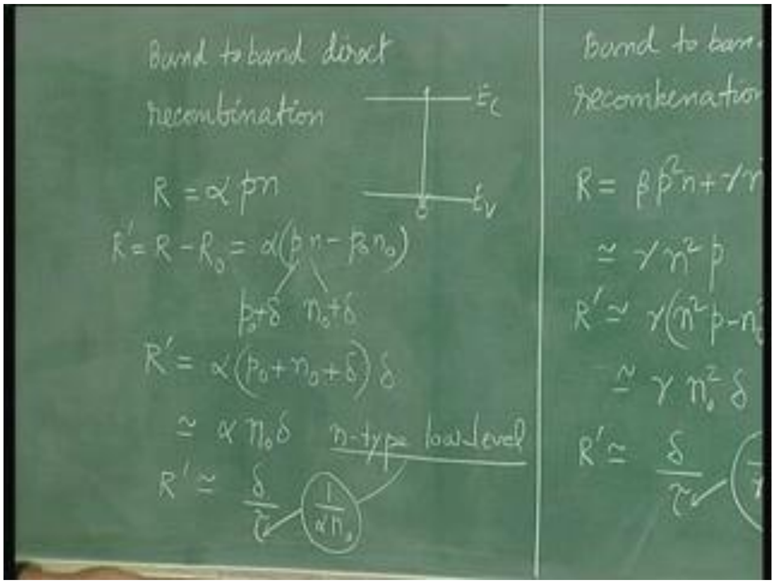

Let us start with band to band direct recombination. Here the electron is falling from the conduction band to valence band straight away. Now this kind of recombination depends on the concentration of holes and concentration of electrons. So you can write the recombination rate as R equal to a constant into product of hole and electron concentrations R is equal to alpha pn.

We are interested in excess recombination rate R prime that is given by recombination rate r minus recombination rate under equilibrium conditions R_0 which can be written as alpha(pn minus p_0n_0) where these are the equilibrium concentrations. Now here the p is equal to p_0 the equilibrium concentration plus alpha that is the Excess Carrier concentration and here n is equal to n_0 equilibrium concentration plus alpha that is the Excess Carrier concentration.

Please note here that the Excess Carrier concentration of holes and electrons is the same and that is how we are using the symbol alpha**.** This can be simplified and we will obtain

R prime is equal to alpha(p$_0$ plus n$_0$ plus alpha)alpha. So what is happening is this p$_0$ n$_0$ product term is getting cancelled when you multiply these two. Now if you take an n-type sample under low injection level then the p$_0$ is a minority carrier concentration it can be neglected and also alpha is much less than n$_0$ that is a meaning of low injection level. So this equation can be approximated as alpha into n$_0$ into Excess Carrier concentration. Finally we write the excess recombination rate is given by Excess Carrier concentration by a time constant and this time constant is given by 1 by alpha$_0$. So this is the time constant of direct band to band recombination and we can also call this as the lifetime for direct band to band recombination.

Very clearly this shows that since alpha is constant and n$_0$ is the equilibrium concentration of majority carriers this is also a constant for a material and therefore the excess recombination rate is proportional to Excess Carrier concentration. So this is how one can derive the fact that excess recombination rate is proportional to Excess Carrier concentration in the case of band to band direct recombination.

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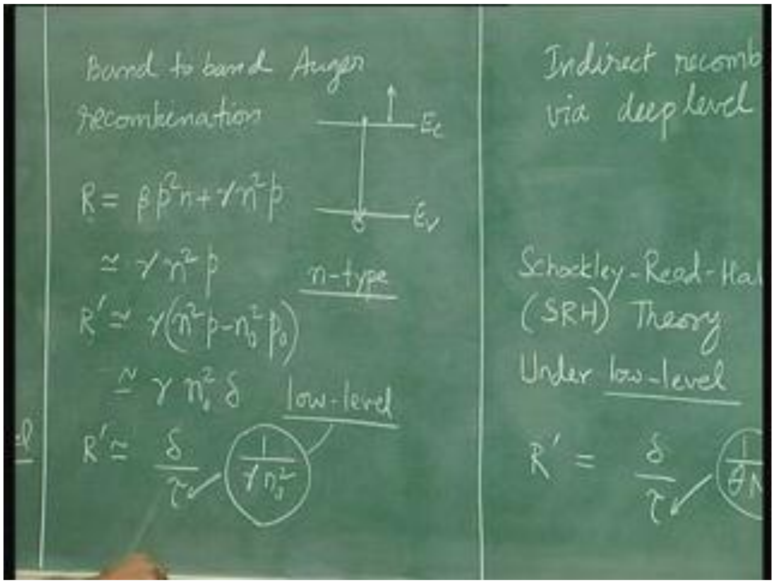

Band to band Auger
recombination

$R = \beta p^2 n + \gamma n^2 p$

$\simeq \gamma n^2 p$ n-type

$R' \simeq \gamma(n^2 p - n_0^2 p_0)$

$\simeq \gamma n_0^2 \delta$ low-level

$R' \simeq \frac{\delta}{\tau}$ $\boxed{\frac{1}{\gamma n_0^2}}$

Indirect recomb
via deep level

Schockley-Read-Hal
(SRH) Theory
Under low-level

$R' = \frac{\delta}{\tau}$

Let us consider another kind of recombination which is present and this is the band to band Auger recombination. In this case an electron is falling from conduction to valence band and the energy and the momentum is being given away to another free electron whose energy increases. Now, the energy can also be given away to a hole in which case you will have a whole increase in energy. So what we have shown is for an electron it can also happen for a hole. This is called the Auger recombination process.

Since here three particles are involved that is this electron, the hole and the third particle which is an electron here or it can be a hole also as we said so therefore we can write the recombination rate in this case as proportional to p square n that is hole recombining with electron and giving energy to a hole or the hole recombining with an electron and giving energy to another electron. So electron electron hole process and hole hole electron process so r can be written as equal to a constant into p square n plus another constant i to n square p. So we are assuming that the constant associated with these two processes are different that is the hole hole process and the electron electron process.

Now, if you consider n type material then the above equation can be simplified to n square p because p will be the minority carrier concentration and so p square n term will be very small compared to n square p term. Now we proceed further and write the expression for excess recombination rate. This is given by gamma into n square p minus n_0 square p_0 the equilibrium concentrations of electrons and holes. And as we have done in the case of the direct band to band recombination we can simplify by substituting p equal to p_0 plus alpha n is equal to n_0 plus alpha and canceling out the terms you will get this relation where this will simplify to this particular equation clearly showing that excess recombination rate is proportional to Excess Carrier concentration for low level conditions.

This simplification we are talking about is for low level conditions and we can write this excess recombination rate finally as alpha by time constant where that time constant is 1 by gamma n_0 square so this is the lifetime associated with the Auger recombination under low injection level. So please note that while the direct recombination lifetime is inversely proportional to majority carrier concentration the Auger band to band recombination lifetime is inversely proportional to the equilibrium majority carrier concentration square.

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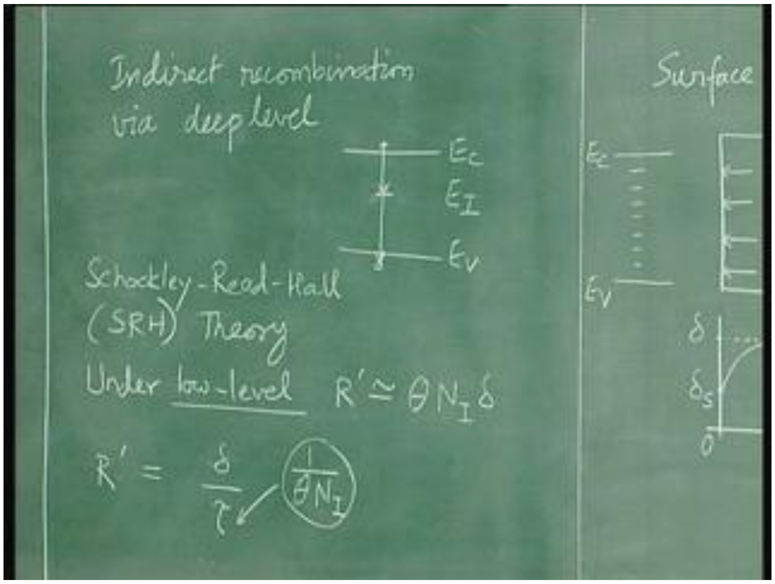

Finally let us take up another important process of recombination the indirect recombination via deep level. So electron is falling into a deep impurity level or deep defect level and then from that defect level it falls on into the valence band and recombines with the hole, this is the process. The Physics of this process is somewhat more complicated than the band to band radiative or direct recombination process and band to band Auger recombination process which we have just now discussed. We will give the result of the theory which was given by Shockley-Read-Hall called as the SRH theory.

As per this theory under low injection level the excess recombination rate will turn out to be proportional to the Excess Carrier concentration and the concentration of the deep impurity or deep level i.e. this which is $N_{I,}$ where i stands for impurity or defect. So we can write this in a simplified form as this R by equal to Excess Carrier concentration by tau which is a lifetime for SRH recombination under low injection level that is 1 by theta N_I the deep impurity concentration. This constant theta consists of a term reflecting the location of the energy of this impurity level. So it is to be emphasized that if this particular energy level is close to E_c or E_v then the theta will be such that the recombination rate will be very low. So recombination rate will be high or this impurity level will be effective in giving rise to recombination only if the impurity level is somewhere near the middle of the energy gap. In any semiconductor the recombination rate will depend on all these three processes and some other processes also. We have discussed the three dominant processes.

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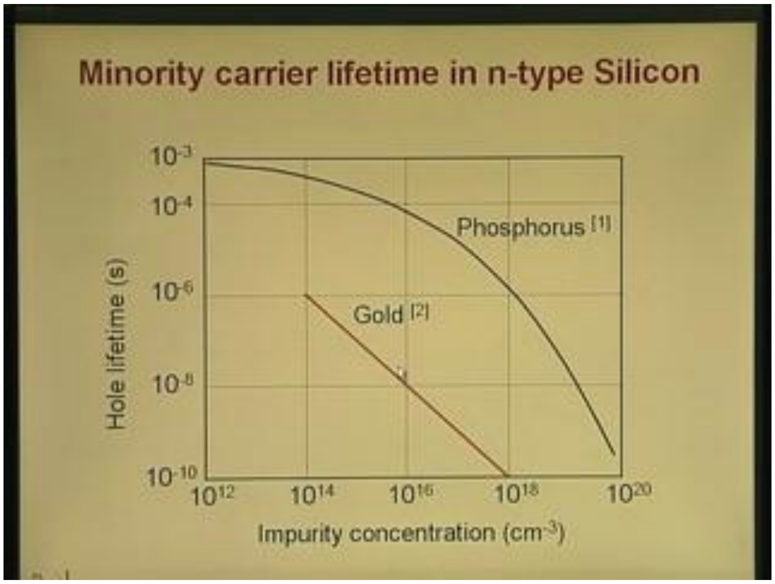

Minority carrier lifetime in n-type Silicon

Let us see how all these processes contribute to a lifetime in n-type silicon. So an n-type silicon as shown here as you change the phosphorous doping the lifetime changes from about a millisecond at 10 to the power 12 or very low doping to about 10 to the power minus 10 i.e. 1 nanoseconds or 100 picoseconds at about 10 to the power 20 by cm cube doping. So this is the curve representing the variation in lifetime as a function of phosphorus concentration. This lifetime is due to the direct band to band recombination as well as band to band Auger recombination. So two processes together contribute to this lifetime and it also contains a little bit of the effect of the SRH lifetime or recombination through deep levels because as you increase phosphorus doping some defects are created unintentionally in the crystal.

Some components of the SRH recombination is also present in deciding this particular curve. When you dope this n-type silicon with gold which is a deep impurity then the lifetime falls drastically. And as you can see by a straight line behavior the lifetime falls as inversely related to the gold doping concentration and the fall in the lifetime is tremendous. You can see for example at 10 to the power 16 from about 10 to the power minus 4, it falls to 10 to the power minus 8 so four orders of magnitude. This is how Gold introduces the deep level and creates the Shockley-Read-Hall recombination starts dominating and that reduces the lifetime like anything.

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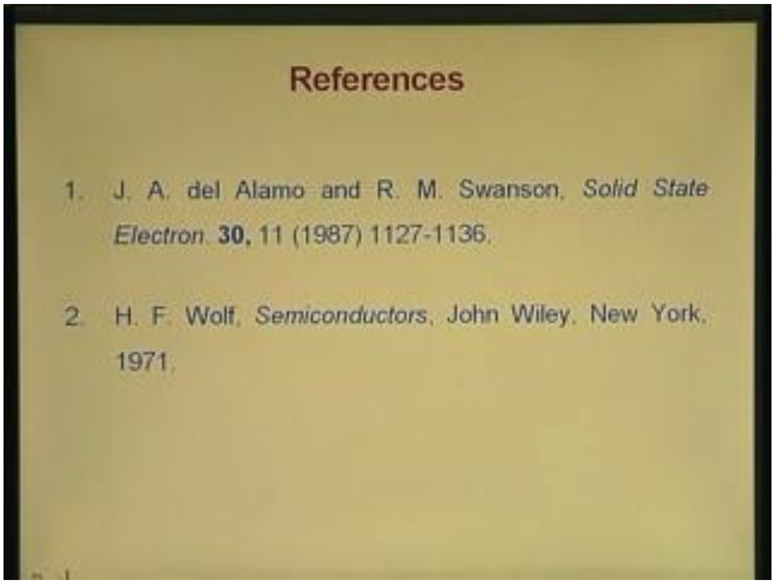

References

1. J. A. del Alamo and R. M. Swanson, *Solid State Electron.* **30,** 11 (1987) 1127-1136.
2. H. F. Wolf, *Semiconductors*, John Wiley, New York, 1971.

This data is obtained from these references in Solid State Electronics 1987 and from a book on semiconductors published by John Wiley New York and authored by Wolf. Finally we will discuss the important concept of surface recombination.

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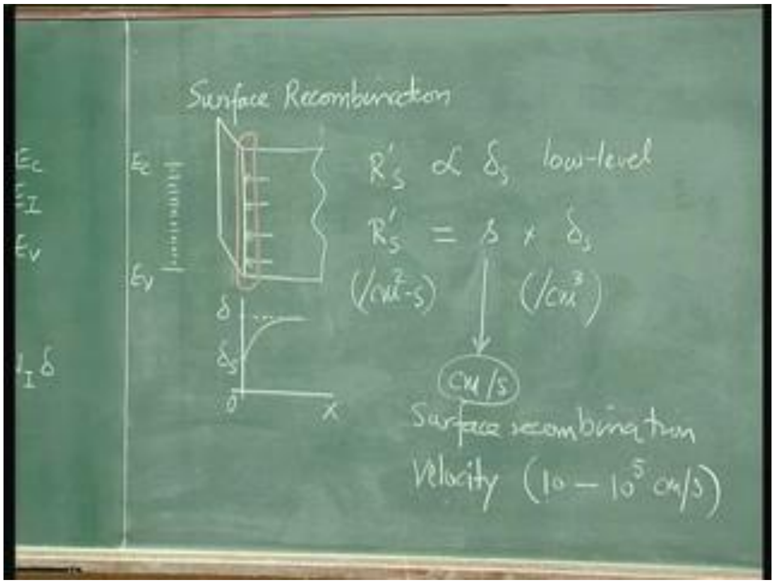

Any semiconductor at the surface has a high recombination rate than in the bulk. This is because the surface is prone to impurities. Also, because the surface represents the disruption in periodic atomic potential a large number of states are created with in the energy gap in a region near the surface. If you take the energy band diagram of this region near this surface you will find that within the forbidden gap you have the large number of states. This is the reflection of disruption in the periodic atomic structure. So there are number of states that are near the energy gap and therefore they will reduce the lifetime because of the recombination via deep levels and this is because of SRH.

As per the SRH theory of the recombination whenever the deep waves are present the recombination rate is very high. So if you see the Excess Carrier concentration as a function of distance one finds that the Excess Carrier concentration will drop when it moves closer to the surface. Let us say the Excess Carrier concentration at the surface is alphaS then it can be shown that the excess recombination rate at the surface R primes is proportional to the Excess Carrier concentration at this surface under low injection level conditions.

We will not discuss the derivation of this equation but we will just accept the result. When you convert this proportionality into an equation you will introduce the proportionality constant. Let us see what the dimension of this constant is. The recombination rate at the surface has dimensions of per cm square by s where we are talking of per centimeter square of this area of this surface at which recombination is occurring. The Excess Carrier concentration has the dimension of per centimeter cube. So naturally the constant will have dimensions of centimeters per second. This is the dimension of velocity and that is why this particular constant is called surface recombination velocity.

Therefore the excess recombination at the surface is characterized by this particular velocity called surface recombination velocity. Its value ranges from 10 minus 10 to the power 5 cm by s. A low value represents a very clean surface whereas high value represents a very bad surface. Now towards the end of discussion let us see the topics we have covered in the last two lectures.

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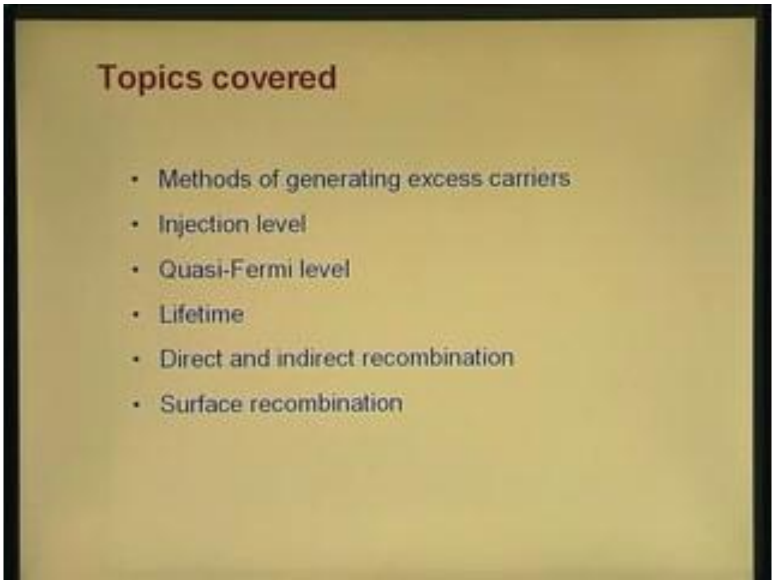

Topics covered

- Methods of generating excess carriers
- Injection level
- Quasi-Fermi level
- Lifetime
- Direct and indirect recombination
- Surface recombination

First we discussed the methods of generating Excess Carriers, then we discussed the concept of injection level, then we discussed the Quasi Fermi-level. We spent a lot of time on the important parameter that characterizes transient response i.e. the lifetime. We discussed the various recombination phenomena such as direct and indirect recombination which decides lifetime in a semiconductor and finally we discussed the aspect of surface recombination.