Semiconductor Device Modeling and Simulation
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Lecture - 44
Generation-Recombination

Hello. Welcome to lecture number 44.

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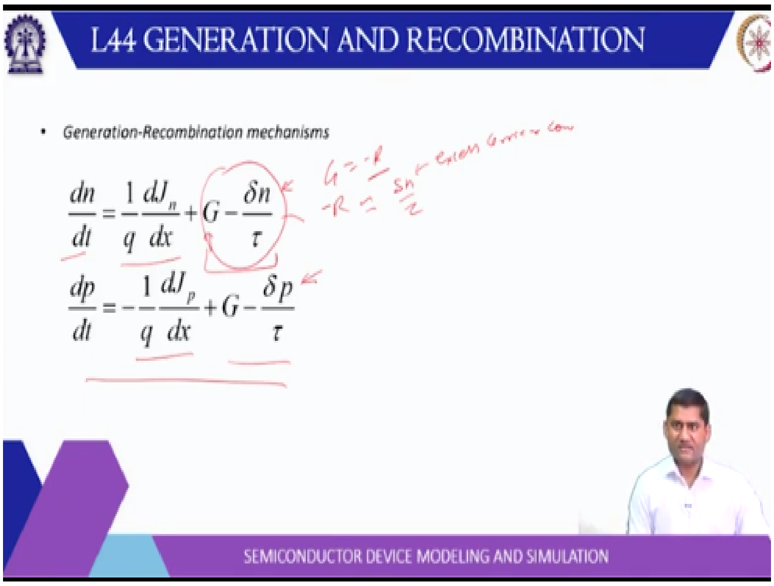

So in this lecture, we will discuss about the generation recombination processes. As we have seen in drip diffusion model that in the conduit equation there is a term here. So dn by dt is the rate of change in the number of electrons is equal to the rate of the gradient of the current density plus generation minus recombination. So this portion is represented in different ways in different text.

So the idea is that there is generation term which could be due to external forces and there is a recombination term. And sometimes this generation is the negative of the recombination. So this can be simply replaced by some minus recombination term. As we will see that generally the processes that cause the generation, their reverse process cause the recombination.

So they are basically you know same expression give you both. When it is positive let us say it is recombination. When it is negative it is generation and so on. And generally, we also represent some kind of carrier lifetime and therefore this recombination is also written as delta n by tau where delta n is the excess carrier concentration, excess carrier concentration and tau is the lifetime.

So how long that actually excess carrier survives. So there are different processes. Similar expression holds for the hole also where dp by dt is again negative gradient of the hole current density plus generation minus recombination. And here we have used different terms because you know generally delta n is equal to delta p, but in some scenarios, it is possible that you know they may not be equal. So we have used separate delta n delta p for both the expressions.

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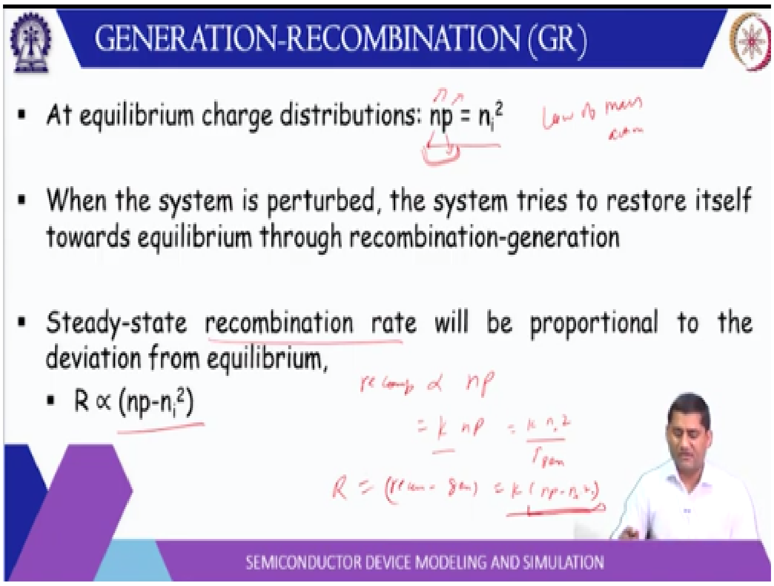

Now at equilibrium this product np product is n i square. That is a equilibrium property and we also call it law of mass action. Now, when we part of the system, so when we you know somehow increase the n or increase the p or decrease the n or decrease the p, then what happens accordingly a generation come into the picture or a recombination term will come into the picture.

If we increase this np product, then the recombination process will basically become more. So there will be net recombination. For example, if you consider a depletion region. Then you reduce this np. Then np perturbed is less than n i square. Then to compensate for the loss of carriers there will be some generation will take place there.

So we can say that in a steady state, the net recombination rate is product to the, this is the difference of np product minus n i square. So or we can say that recombination is proportional to np product. Now in equilibrium this np product is n i square. So we can say that recombination is equal to some coefficient k times np. Now in equilibrium, this is equal to k times n i square.

So then we can say, in equilibrium this is equal to k n i square. So that means this is the generation rate. So the net recombination is recombination minus generation. So that is k times np minus n i square. So in almost all the processes we will discuss this term will be there np minus n i square. So recombination is proportional to np minus n i square.

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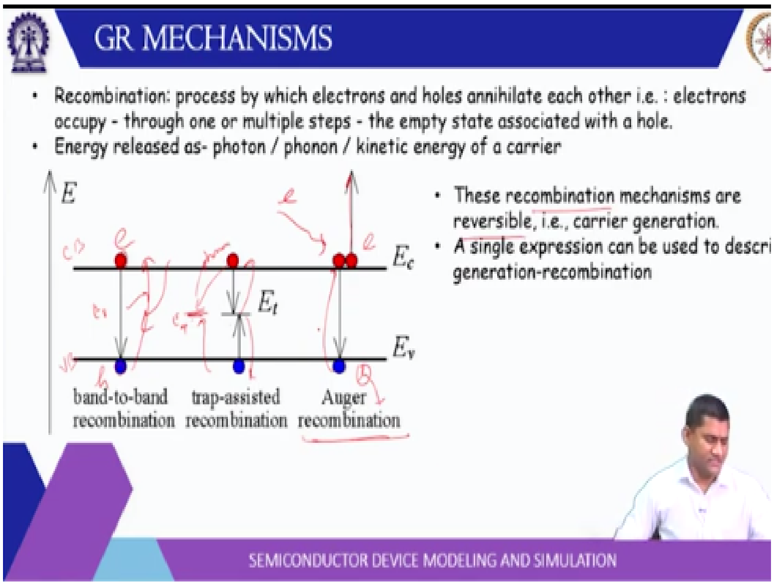

Now different types of recombination. As you know that in semiconductor, there is a conduction band and there is a valence band. And recombination consists of electron from the conduction band and hole from the valence band they combine and they annihilate each other. So net effect is that there is a reduction in the electron concentration. There is a reduction in the hole concentration.

Now this process can happen directly that you know electron from the conduction band directly jump onto the hole in the valence band and they annihilate. Or it can happen in different steps. One possibility is that there may be some impurity level here. So electron is captured by this and hole is captured by this level and they recombine here. Another possibility is that when this electron make a transition to the hole, now what is happening?

This will, this process will release certain energy because then when these electron and hole combine this process will release certain energy. So that energy has to be taken by some other carrier. So what is happening here in direct recombination it can be taken by some particle which has this much energy equal to the bandgap.

In trap state or recombination through energy level in between it is possible that this energy will be taken by some of the particle, let us call it phonon or crystal vibration. And in one such process, this energy is taken by another particle. It could be electron or it could be hole. So if it is taken by electron it will move here, if it is taken by hole it will move here. And they have different names.

This is called auger recombination. Now as you can notice here, there are three particles involved. So this recombination takes place when the number of particles are more. Now these recombination mechanisms are reversible. So there is a same way they are recombining, in a similar way they can also cause a generation of carriers.

So it can absorb a photon and then this electrons will make a transition from valence band to conduction band and create an electron hole pair. Same way this phonon can give the energy so it can release electron here, it can release a hole here. And in auger recombination there is a possibility of this high energy electron comes here and hits knocks the hole from valence band to the conduction band thus create a electron hole pair. So these are reversible processes.

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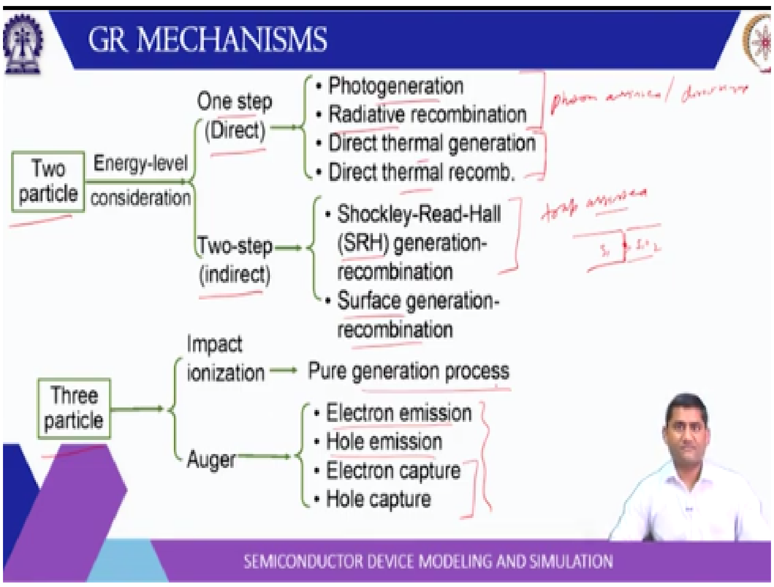

Now let us go through them one by one and before that let us categorize them. So overall they can be categorized into process involving two particles, process involving three particle. So in two particle they can be direct or they can be indirect. In direct process that means in a single step process, there can be a photon assisted generation, we call it photo generation.

Or when they recombine they give away a photon. So that is called radiative recombination. And I think we have already pointed out that this is possible in case of, this is more probable in case of direct bandgap semiconductors. Then it is also possible for smaller bandgap materials that thermal energy may be enough to make a to excite electron from the valence band to the conduction band and give away the heat instead of the photon.

So this is direct band to band through thermal processes. Then two-step process is basically trap assisted. So this could be due to a impurity atom which create a energy level in the bandgap region. Then we have a name Shockley-Read-Hall recombination model. So they can be trap assisted generation or they can be trap assisted recombination also.

Then at the interface of the semiconductor, let us say silicon and silicon dioxide, because there is a termination of the semiconductor surface there may be energy states here and they may act as a trap. So for them we have surface generation or recombination. So that is also possible when there is a semiconductor getting terminated at certain distance. Then three particle process is the auger generation recombination.

So it can give the energy to electron, so have electron emission. It can give away the energy to the hole so it can be hole emission or it can also capture a hole and electron. And opposite of that is impact ionization. So here high energetic carrier could be electron, could be hole and it generates the pair of electron hole in the process.

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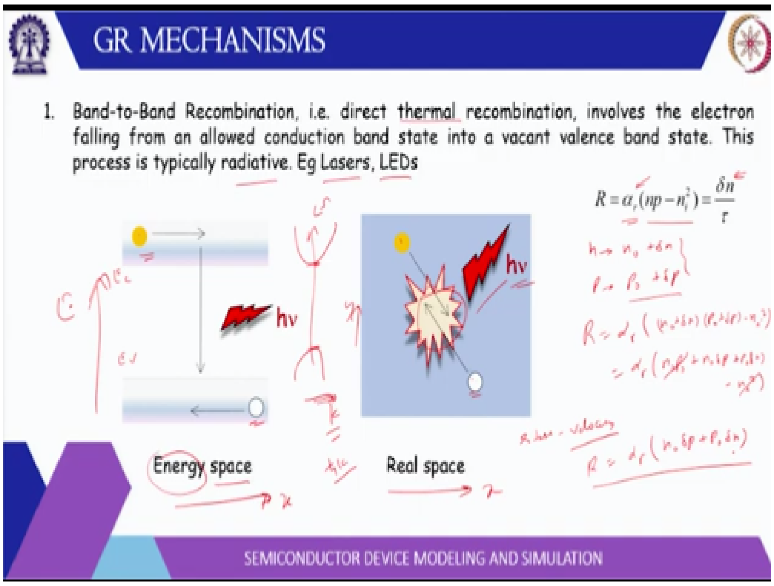

Now the first is the band-to-band. Now there are two pictures here. One is in the space. So let us say this is some position x. Then this is real x, this is position x. This is energy space. So this axis is energy and x axis can be accessed basically or if you draw this kind of diagram, then this can be k vector. So there are two types of diagram that we have discussed. One is the band diagram, where we plot this energy.

Now this energy is the lowest of this conduction band and the top of this valence band, which we call E C and E V and this versus position. Another is E K diagram, where y axis is the energy and x axis is the k vector. So here we see two picture. One is the energy space where y axis is the energy. Another real space where this is the x y you know the region of the space basically.

Now when these electrons and holes they come nearby. So physically they are near, but these electrons are in the conduction band and these holes are in the valence band. So when we see the band diagram, it appears that they are actually separated. No, they are not separated, they may be in the same region of space. It is like you know when we say E K diagram, then k is what? k is a wave vector.

So h bar k is the momentum. So it simply means the velocity. So the state is here basically some kind of a relation with the velocity. So different velocity, electron with different velocity have different states basically. So these electrons and holes they come in the same region of space then they can recombine basically plus these electron holes they collide. So then it is possible that they may recombine and then give away the photon.

So in physical space what is happening these electron and hole they are combining and in energy space they are falling from their respective energy levels and giving away the excess energy as photon. So this is the direct process, okay? Again it could be thermal in a smaller bandgap material, but for moderate bandgap material it is mostly radiative. So that means it involves a photon rather than a phonon.

And this is the basis for designing the lasers and LED structures. Now in this case, again we can define some constant alpha, usually it is called absorption coefficient and the net recombination is alpha coefficient times np minus n i square. And that we can equate to the delta n by tau. So delta n is the excess carrier. Now what is excess carrier? Your n becomes n naught equilibrium value plus delta n.

And let us say your p becomes equilibrium value p naught plus delta p. So this delta n and delta p are the excess carriers. Now let us consider this is the new concentration. So the recombination rate is given by alpha r times n naught plus delta n times p naught plus delta p minus n i square. So if you expand it, you get n naught p naught plus n naught times delta p plus p naught times delta n minus n i square.

Now n naught p naught will be n i square. So your recombination rate is actually alpha r times n naught delta p plus p naught delta n. Now we can consider two types of injection level. One is called high level injection other is called low level injection.

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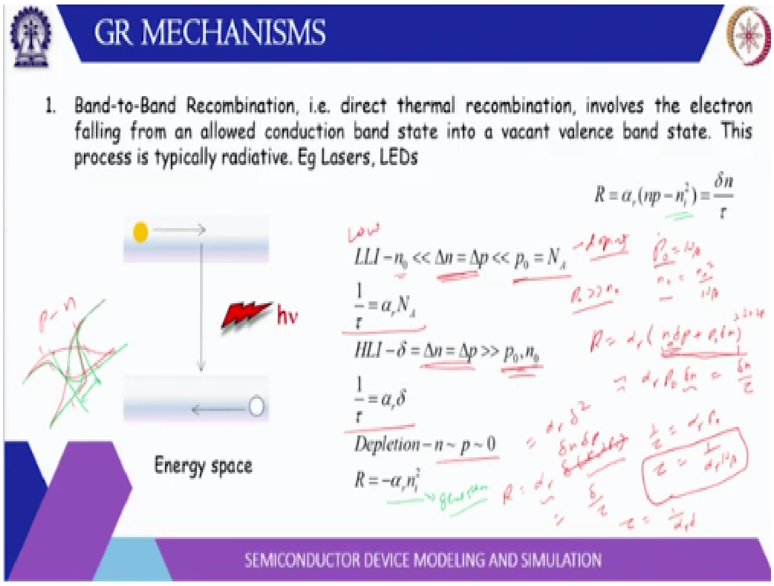

So this is low level injection. Now low level injection the condition is that delta and delta p is much less than the doping. So this n, we are considering the p type material. You can also consider n type material then it will come n naught equal to nd. So injection or the excess carrier is much less than the doping concentration. But it is much larger than the minority carrier concentration.

So this is your let us say p type material. So for p type p naught is equal to doping at room temperature and n naught will be n i square by p naught that will be N A. So this low level injection is the excess carrier concentration is between them, between the majority carrier concentration and more than the minority carrier concentration. So the expression we wrote R is equal to alpha r times n delta p n naught delta p plus p naught delta n.

Now in this case if you see the p naught is much larger than n naught because this is the p type material. So you can simplify this as alpha r times p naught delta n because this n naught delta p you can ignore. So if you compare this thing with delta n by tau then you find out that 1 over tau is alpha r times p naught or tau is equal to 1 over alpha r times p naught. And p naught is actually N A.

So this is your carrier lifetime for low level injection. In high level injection this delta and delta p is much larger than p naught n naught. So this expression will actually become R will become alpha r times, delta and delta p they are equal, they are equal to delta. So delta we can take outside and here we can write n naught plus p naught.

And if you equate this is delta by tau. So what do you get? Tau is 1 over alpha times n naught plus p naught. No actually we have ignored this plus delta n delta p term here. See here. Okay there is plus delta n delta p term here. That will also be there. So for low level injection we can ignore this term delta n delta p, but for high level we cannot ignore because now delta and delta p is much larger than n naught p naught.

So in fact, these two terms are small in front of this delta n delta p. So what we can write here? So let me correct it, alpha i times delta n delta p. So if you compare this by delta by tau what you get here was delta n is equal to delta p. So you can write it as alpha r times delta i square. Now if you compare this thing delta by tau you will get tau is equal to 1 over alpha r delta. So this is your lifetime for high level injection.

Then in depletion region np are small especially if you recall that pn junction in depletion region. There are actually two types of depletion region. One is when you do not buy a set. So in this region, this np they are actually smaller than the doping concentration. But when you do reverse bias, it actually concentration goes like this. Let me use different color.

So for reverse bias, this concentration goes something like this. So this region if you see here, the concentration is very small. You can almost you know we can say it is zero. So if n and p are equal to zero, then your r becomes minus alpha r times n i square. So this is simply it has a negative sign. So negative sign means it is simply a generation case.

Because what is happening inside the semiconductor, both germination and recombination are balanced. So they are equal in equilibrium. So whenever you know one part is disturbed, the other part react basically. So if you increase the np the recombination will increase, if you decrease the np then generation will take over.

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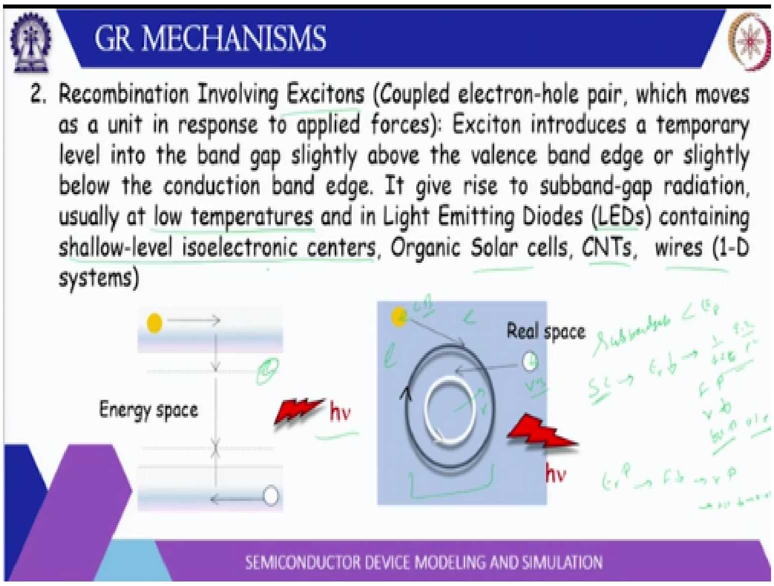

Then second mechanism is basically involving the excitons. Now excitons are very interesting particle. They are combination of electron and hole. So this is the electron and this is the hole. And they are somehow nearby to each other and by electrostatic attraction force they are bound. But they are not recombined. So when they bind, there is some binding energy.

So when they will recombine the energy radiated will be smaller than the bandgap energy, because why? Because this electron is in the conduction band, this hole is in the valence band, but in the physical regional space, they are attracted to each other due to the electrostatic attraction force and they are forming a single unit.

So when they move around, so that means, some kind of the net charge they carry will be zero because electron is positive, electron is negative hole is positive. So they do not carry any charge as such, but they can move around in the region of space and when they recombine, usually they are radiative and that energy of that radiation it has to overcome the energy required to break this binding and then of course make a transition from conduction band to valence band.

So they usually give sub bandgap radiation. Sub bandgap means less than the bandgap energy. Now their nature depends on the host material. For example, the piece of semiconductor will have certain dielectric constant. So let us say epsilon r, let us say this is small, let us say low dielectric constant. Then the electrostatic attraction force, we know this is proportional to 1 over 4 pi epsilon q 1, q 2 by r square.

So this epsilon is small. So the force will be, attractive force will be more. And when the attractive force is more they will be more close to each other. So the radius if you see here the radius will be less and corresponding binding energy will be you know little higher, usually 0.1 or so electron volt. So this is in low light dielectric constant materials.

When you have high dielectric constant then of course, 1 over 4 pi epsilon so the attractive force will be less. That means, their radius will be more and the binding energy will be smaller, usually 0.1 electron volt and so on. So another things you may be wondering you know when they are attracted, what is stopping them from recombining.

Now in a semiconductor these electron holes are not alone. So there are other surrounding electrons and holes. So this electron is attracted by this hole, but there is repulsion from other electron. So this force is some kind of balanced. So that is why this exists. But these exist a low temperature usually. So this is the dominant mechanism at low temperature.

And then of course, light emitting diodes and solar cells carbon nanotubes or 1-D nanowires, there this phenomena can be seen. Now usually it is found in shallow level isoelectronic centers. Isoelectronic means the center the impurity. It has the same electronic configuration as the host material, it is isoelectronic. So this is another recombination mechanism involving excitons.

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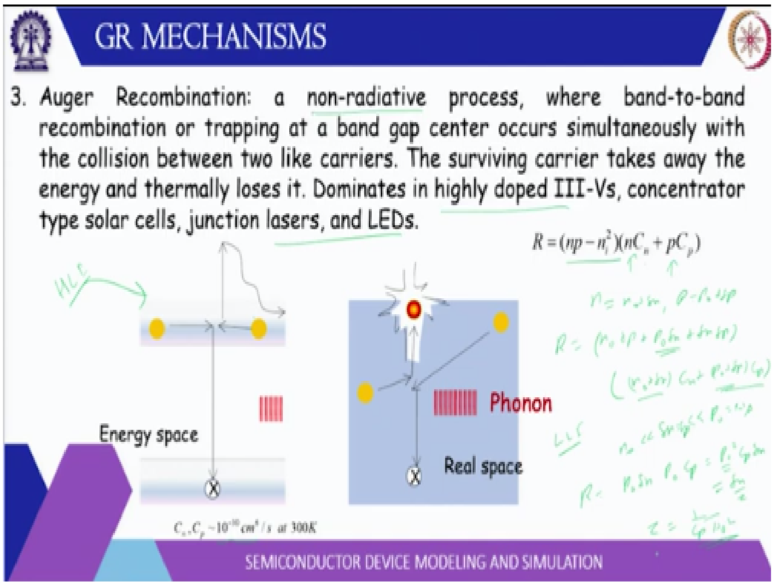

Then there is auger recombination mechanism. As we have discussed it denotes three particle. So your recombination is now np minus n i square multiplied by some coefficient. So now this third particle could be electron. So then we have coefficient C n times n. Third particle could be a hole. Then we have coefficient C p times p.

And the typical values of this C and C p routers are 30 centimeter power 6 per second at 300 Kelvin. So these are typical values. These values are listed for different materials, you can find out. Now here also we can again check for high level injection, low level injection. Now one thing to notice here, because the energy is taken by third particle, so this is a non-radiative process.

So there is no phonon emission here. So this is basically something unwanted in case of lasers and LEDs because we do not want the energy to be taken by other carrier. We want all the energy to be emitted as photons. So this auger recombination takes place when band-to-band recombination is there and the third particle is taking away that energy.

So that means number of carriers has to be large, because it is basically if you see it is proportional to n square p and p square n. So more number of particles are involved. So this process will dominate in case of highly doped materials or if not doping, then these high number of carriers are injected. So some kind of high level injection is there, then also it is possible.

Now again if you compare the non-equilibrium case, let us say n is equal to n naught plus delta n p is equal to p naught plus delta p and if we substitute here R is equal to then of course, you can write n naught p naught is n i square so they will cancel. So n naught delta p plus p naught delta n plus delta n delta p times n naught plus delta n times C n plus p naught plus delta p times C p.

So again we can consider low level injection and high level injection. So let us consider low level injection. Let us say this is p type material which is equal to p naught equal to na, is much lesser than delta n delta p. And this is much larger than the minority concentration, which is n naught. So we substitute here. Then among this, this will be the highest. So your R is equal to p naught delta n.

Then among these two C n C p are of the same order. So you can just take this p naught plus delta p which will be again p naught. So this will be p naught times C p. So this is p naught square C p times delta n. So we compare this to delta n by tau. You will get tau is equal to 1 over C p times p naught square. And p naught is basically your na.

So here you see this carrier lifetime is proportional to 1 by na square. So for high doping, this carrier lifetime will be even smaller, because there is high probability of auger recombination.

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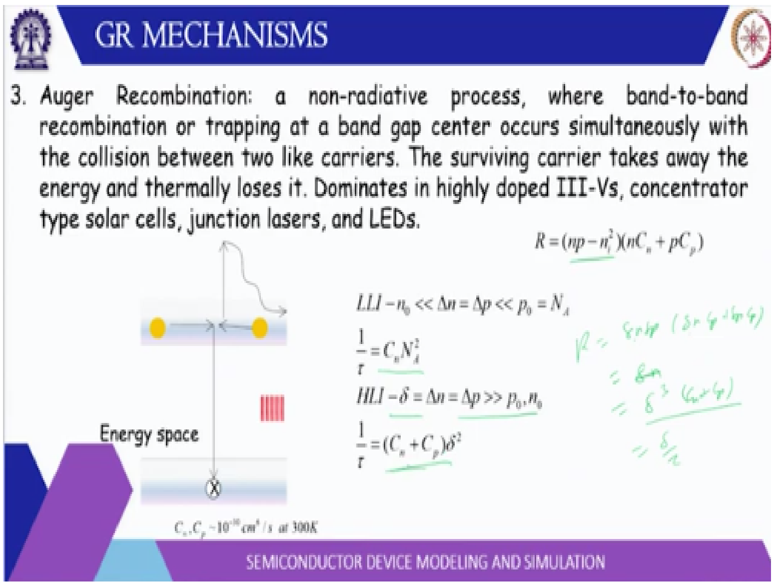

So 1 by tau is C times n square, doping square. For high level injection delta n delta p are quite large. So R can be written as delta n delta p, the rest of the terms are negligible, times delta n C n plus delta p C p because n naught p naught are much smaller than delta n delta p. So this will be something delta n and delta n delta p are equal so let us write them all of them delta.

So this will become delta square and delta cube. So delta cube C n plus C p. So if you compare this thing delta by tau, so you get tau is around delta square C n plus C p. So this will be your carrier lifetime for high level injection and this is basically again dependent on this coefficient for C n and C p.

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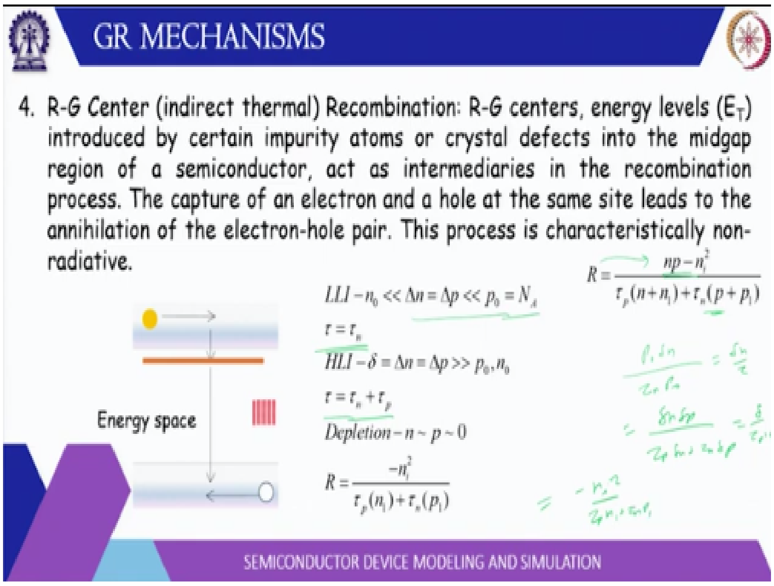

Then another recombination mechanism is based on recombination Generation Center is also called trap assisted recombination. So here recombination takes place through this trap energy level E T. Now this trap energy level is formed by impurity atoms. So there can be a doping of let us say some you know in silicon usually gold acts as a trap energy level and this usually in the middle.

It should be shown somewhere here. It is usually in the middle of the bandgap, then it is more efficient. And when it is near to the bandgap it is called we call it shallow level. So they are not so efficient in recombination. Now if you see here this trap level it can capture electron so the electron can you know move around this impurity. So these are trapped impurity level.

So this electron can come around here and it can also capture a hole. So hole can also come here and they can recombine. So in terms of space they are near to this trap energy or means the trap level. And there they recombine and there recombination is given by np minus n i square divided by tau p times n plus n 1 plus tau 1 times p plus p 1.

This expression we will derive and based on this expression you can also find out the case for low level injection and high level injection because low level injection will be delta n delta p much less than p naught. So if you substitute here this will be that is the p type material. So it will be p naught times delta n. And divided by again these two, this will be dominant because p is more.

So tau n times p naught. So if you see this will be delta n by tau. So this is tau is tau n for low level injection. For high level injection delta and delta p are more. So this will be delta n times delta p, rest you can ignore divided by tau p times delta n plus tau n times delta p. And delta and delta p are equal. So you can write delta by tau n plus tau p. So this is 1 over tau n plus tau p.

So this is the lifetime for high level injection. And of course for depletion region your np is almost zero. So numerator becomes minus n i square and it is divided by tau p times n 1 plus tau n times p 1. So that is what you get.

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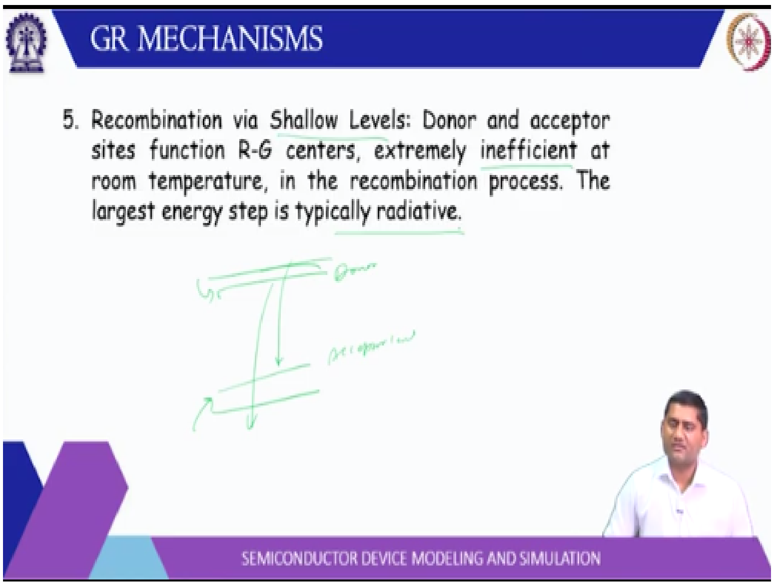

And the fifth mechanism is via shallow levels. So shallow levels are somewhere near the band edge. So it could be near the conduction band edge or it can be near the valence band edge. So now what are the energy levels near the conduction band edge? They are called donor levels. The energy levels near the valence band edge is called acceptor levels.

So they can also act as a recombination center, but usually they are inefficient at room temperature for the recombination processes and even in them the largest step could be radiative usually. So we have covered, we have discussed the, we have reviewed these different recombination mechanisms. So in next lecture, we will further continue regarding the, you know how these are measured and how do we derive this SRH or the trap-assisted recombination model. So thank you very much.